VOL. 4 No. 6 JUNE 1939

Philips Technical Review

DEALING WITH TECHNICAL PROBLEMS
RELATING TO THE PRODUCTS, PROCESSES AND INVESTIGATIONS OF
N.V. PHILIPS' GLOEILAMPENFABRIEKEN

EDITED BY THE RESEARCH LABORATORY OF N.V. PHILIPS' GLOEILAMPENFABRIEKEN, EINDHOVEN, HOLLAND

A MILLION VOLT X-RAY TUBE

by J. H. van der TUUK. 621.386.1.027.7 : 615.849

In the use of X-rays in medical therapy there is at present a tendency to use higher and higher voltages. The very hard X-rays so obtained (comparable with γ-rays) have the advantage of a much higher efficiency, a higher percentage depth dose and less scattering. In this article the problems which are encountered in the construction of X-ray tubes for very high voltages will be discussed. A description is then given of a million volt X-ray tube which was developed in the Philips X-ray laboratory and is now in use in the Cancer-Institute of the Antoni van Leeuwenhoekhuis in Amsterdam. In contrast to the experimental tubes for this voltage which have for example been used in the United States, this tube works without a pumping system and has a length of only 2.40 m. The radiation dose obtained is equivalent to that of about one kilograms of radium. In conclusion several properties of the radiation, as well as the necessary protective measures are discussed.

In the application of X-rays in medical therapy, especially in the treatment of malignant growths (cancer, for example), use is made of the destructive action of the rays on tissues. The γ-rays of radium are also used for the same purpose. There is no fundamental difference between X-rays and γ-rays from the physical point of view: γ-rays are very hard X-rays (of very short wave length), which could be excited artificially if an X-ray tube for a sufficiently high voltage were available (for the hardest γ-rays of radium about 2 million volts). Since, however, the nature of the influence of the rays on the tissues is only very imperfectly known, it is reasonable to suppose that the biological action of the γ-rays may differ from that of the softer X-rays which are obtained for instance with 200 kV.

Such a specific action of very hard X-rays has not yet been convincingly proved. Very hard X-radiation has, however, various properties which allow one to expect somewhat more favourable clinical results than with the softer (200 kV) rays. The efficiency in the process of excitation of the rays increases very much with increasing voltage of the tube; furthermore the percentage depth dose in the treatment of patients, *i.e.* the ratio of the dose 10 cm below the skin for example to that at the surface of skin, shows considerable increase, while at the same time less radiation is scattered to the sides and backwards, so that the surrounding healthy tissue and the skin are less exposed to attack. These advantages are sufficiently important to justify medical interest in X-ray tubes for very high voltages, even without any specific effect of the very hard rays. In this article we shall briefly describe the development of these tubes, A detailed description will be given of a million volt X-ray tube which is now in use at the Cancer-Institute in the Antoni van Leeuwenhoekhuis in Amsterdam.

Constructional Problems with X-ray tubes for very high voltages

If an attempt is made to load an ordinary X-ray tube, such as is used in diagnosis or structural analysis, and is intended for not more than 100 kV, with higher voltages, undesired phenomena occur inside as well as outside the tube. Outside the tube flash-over may occur in the air between the electrodes, or creeping discharge along the glass. Inside the evacuated tube independent discharges may occur, resulting in local destruction of the glass or the electrodes. These are the most important difficulties which must be overcome in the construction of X-ray tubes for very high voltages.

For the avoidance of flash-over, etc. outside the tube a certain insulation length is necessary between the parts which are at high tensions with

respect to each other. Inside the tube the situation is more complicated. The greatest difficulties experienced are due to stray electrons which may originate in two ways: by electron bombardment (secondary electrons) and by cold emission [1]).

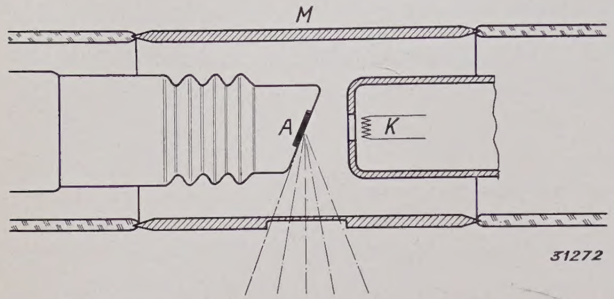

Fig. 1. Diagram of the electrode system of an X-ray therapy tube for 200 kV. The anode A and cathode K are about 1 cm apart. The glass of the tube is replaced by a metal middle section M at the point where the discharge takes place.

When such stray electrons reach certain places in the tube they may cause trouble in various ways. If they impinge on the glass it becomes heated and electrolysis (in the neighbourhood of sealing-in spots) or localized attack or perforation of the glass may occur. The gas atoms still present in the tube are ionized, and this may lead to a flash over between the electrodes. The metal parts, struck by the stray electrons, emit an unwanted X-radiation. In addition to these there are still other effects which are promoted by those already mentioned; for example the heated parts begin to give off gases and thus the ionization is increased; the stray electrons free new electrons from the metal parts; they may also cause a negative charge on the insulated parts of the tube which results in a distortion of the electric field and an increased chance of cold emission, creeping discharge along the surface of the tube or even breakdown through the glass.

The simplest way to give some idea of the manner in which these difficulties were solved, is perhaps to describe a series of tubes in which the voltage has been successively increased.

In *fig. 1* a schematic diagram is given of the electrode system for a tube with which voltages up to 200 kV were reached. The tube itself is sufficiently long to keep the connection points of the high voltage sufficiently far away from each other in the air. The electrodes in the tube, however, are placed relatively close together (about 1 cm at 200 kV) This is desirable in order to prevent the electrons from meeting and ionizing too may gas atoms along their path: the shorter the path of the electrons the less the ionization. For the same reason the tube is rigorously outgassed during construction in order to obtain the best possible vacuum. The glass of the tube is replaced by a metal middle section at the spot where the discharge proper takes place. This part of the tube is most exposed to bombardment by secondary electrons which are liberated at the anode at the same time as the X-rays are excited.

The secondary electrons, which amount to 10 to 20 per cent of the number of primary electrons, are emitted in all directions from the focus, and will for the most part be drawn back again to the anode by the electric field. Since, however, most of them have very high velocities (not much lower than the primary electrons), with the electrode configuration of fig. 1, part of them return only far toward the back of the anode. The tertiary electrons freed there may again prove dangerous to the glass. In order to prevent the secondary electrons from travelling so far back, the form of electrodes shown in *fig. 2* was chosen: the surfaces of cathode and anode are parallel over an area whose diameter is four times the distance between them. It may be demonstrated [2]) that with this configuration all the secondary electrons which leave the focus at the centre of the anode fall back again on the front surface of the anode, and thus cannot leave the space between the electrodes.

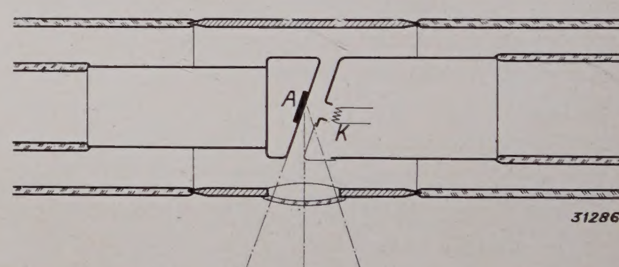

Fig. 2. If the surfaces of cathode and anode are parallel over an area whose diameter is equal to four times the distance between them all the secondary electrons which are formed at the focus are drawn back again to the front surface of the anode. The projecting corner of the cathode is made very thin so that the X-rays can pass through it almost without attenuation.

In this way, as has been stated, voltages of 200 kV were reached. The configuration of *fig.3*, where the greater part of the secondary electrons are captured in a hollow in the anode and the rest fall upon the concave front surface of the anode, gave somewhat higher voltages (about 250 kV). Due to the gradual curvature of the surface of the cathode there are no sharp edges which could increase the density of the electric field or the field

[1]) On the subject of cold emission see for example Philips techn. Rev. 4, 103, 1939.

[2]) A. Bouwers and J. H. van der Tuuk, Secondary electrons in X-ray tubes, Physica 12, 274, 1932.

strength, so that cold emission becomes less dangerous.

The following step was the construction of a tube which was fundamentally a proportionate enlargement of the tube for 200 kV, with double the

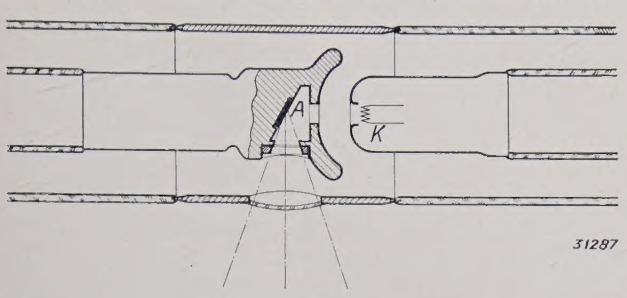

Fig. 3. Electrode configuration for capturing the secondary electrons in a hollow of the anode or on the front surface of the anode. Due to the gradual curvature of the surface of the cathode the chance of cold emission is considerably lessened.

dimensions of that tube. With twice the voltage, *i.e.* 400 kV, the same maximum values of the field strength were reached as with the smaller tube. In static tests this large tube was actually found to withstand 400 kV for a time. In use, however, (*i.e.* with current flowing) the voltage could not be raised much higher than about 300 kV for lengthy irradiations. The secondary, tertiary, etc. electrons in this case apparently had so much energy that, notwithstanding the fact that their number had been decreased in the way described, they still caused too much heat development and giving off of gas, etc. by their bombardment.

An improvement was obtained here in the first place by the introduction of a "getter". A getter is a substance [3]) which combines with, and thus retains, the gases present in the tube or freed by electron bombardment during operation. The higher vacuum obtained in this way was accompanied by two advantages. In the first place the chance of independent discharges in the tube was diminished owing to the decreased ionization, so that the voltage could be raised to 350 kV. In the second place the emission of the hot tungsten cathode was made more stable, which is very desirable in order to be able to control the dose of the X-radiation applied. The greater stability of the emission when a getter is used may be explained by the fact that small amounts of certain gases in the tube may contaminate the hot cathode and temporarily diminish its emission.

As stated above, one of the harmful effects of stray electrons consists of a field distortion due to the negative charging of insulating parts of the tube. Such charging occurred especially in the case of the metal middle section of the tube which surrounds the electrodes. The obvious solution of this difficulty of field distortion was to prevent the potential of the middle section from "oscillating" by giving it a constant potential. If for example anode and cathode are at equally high positive and negative potentials respectively, with respect to earth, then the surrounding middle section can be earthed. By this subdivision of the voltage the tube can never be under more than half the basic voltage, while with an "oscillating" middle section it was possible for this section to assume nearly the cathode potential.The principle of subdivision of the voltage was now carried through further by fastening a partition to the middle section (*fig. 4*), so that the anode and cathode are situated

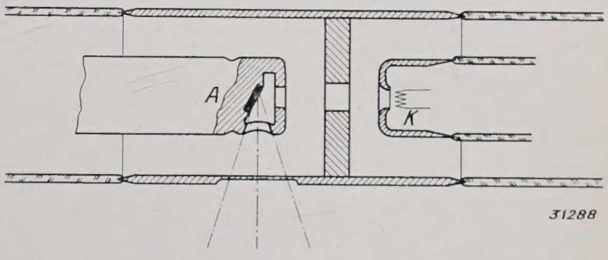

Fig. 4. Electrode system with intermediate partition. The middle section with the partition is given a constant potential which lies halfway between the potentials of anode and cathode (symmetrical division of the voltage).

in two entirely separate spaces, while the primary electron beam is allowed to pass through an opening in the partition. The action of this partition is easily understood: we have already stated that care must be taken to prevent undesired electrons from covering long distances in the tube. In order to prevent the field strengths (cold emission) from exceeding the permissible limit, tubes for higher voltages had to be larger, and at the same time the total path of the electrons was made longer. The intervening partition, however, reduces these paths to the same order as in tubes for half the voltage. Ionization, and with it the danger of breakdown in the tube, is considerably reduced in this way. Moreover the electrons freed by cold emission can no longer reach the anode, but can only bombard the partition, at which point they have only half as much energy. The X-ray tubes constructed on this principle and provided with getters were found easily to withstand voltages up to 400 kV and to attain an entirely satisfactory life at this voltage [4]).

[3]) See for example, Philips techn. Rev. **3**, 296, 1938.

[4]) Such tubes have been used successfully for several years in the institute of Prof. Maisin in Louvain. The tube had a life of from 2 000 to 4 000 hours. *Cf.* J. Maisin and P. Estas, Radiologica **1**, 100, 1937.

By consistent application of the principle of subdivision of the voltage, technical X-ray tubes can now also be constructed for still higher voltages. Two or more tubes each suitable, for instance, for 350 kV are connected in series. In this way an X-ray tube for 700 kV was first developed. This has been described elsewhere [5]). An X-ray tube for one million volts has now been constructed in the Philips laboratory according to the same principle. The details of this tube, which we shall describe briefly, will be readily understood from the explanation given above.

Construction of the X-ray tube for one million volts

Fig. 5 is a schematic diagram of the tube. It may be seen that the three units *1*, *2*, *3* are connected in series. The anodes of all three units are perforated. Electrons emitted by the hot tungsten cathode K and accelerated between cathode and anode of the first tube, enter the hollow anode, travel with constant velocity through the narrow connecting piece into the second tube. They are here accelerated a second time between cathode and anode, and yet a third time in the third tube. At the end of the channel in the third anode the electrons finally strike the target T, where the X-radiation is excited.

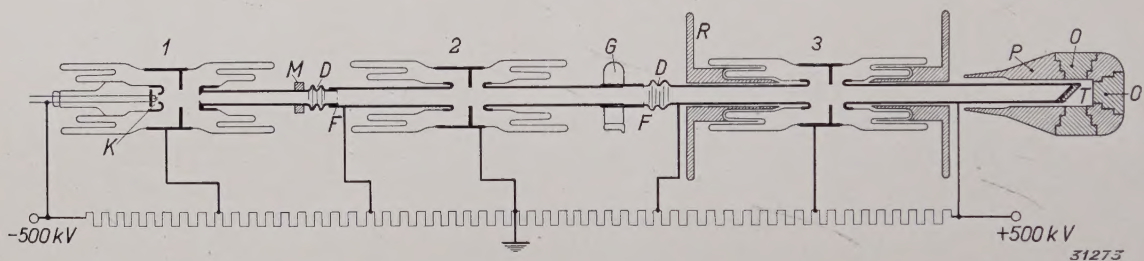

Fig. 5. Diagram of the million volt X-ray tube. The three units *1*, *2*, *3* are prepared separately and evacuated, and then put together. At F metal foil for provisional sealing, K cathode, T target, M focussing magnet, D flexible metal sections, G metal holder with spare getters, P lead jacket for screening the X-rays outside the effective beams, which are transmitted through the window O. The ring-shaped hollows in the double folds of the glass wall of each unit are filled with a "Philite" body R (indicated only in the case of the third unit). The voltage across the tube is subdivided into 6 steps which are tapped from a potentiometer.

The three units are prepared separately, outgassed and evacuated; during these manipulations they are provisionally closed at the ends by thin metal foils. The ends of the tubes are then placed together, as shown in *fig. 6* and soldered. The connection between the vacua in the three separate tubes is brought about simply by melting the foil by bombardment with primary electrons. The fact that it is possible to use this method is due to the use of getters, which absorb the gases freed during soldering and perforation of the foils. Since a good vacuum becomes more and more important with increasing voltage, the ease with which the vacuum is maintained in the tube here described without pumping during operation (it remains 10^{-5} mm Hg) is one of its most important characteristics. It has even been found possible to open the tube, and replace one of the three units by a new one, after which evacuation at room temperature by means of a transportable pump was found to be sufficient to cause the tube to work perfectly again after being sealed off the pump. Several spare getters are introduced into the holder G. These can be brought into action when desired by evaporation.

Another practical and very welcome property of the tube is its relative shortness, which is made possible by the double folds in the glass connections between cathode, middle section and anode of each unit. By this artificial lengthening of the glass insulation creeping discharges along the outside of the glass are prevented, while local direct sparking is prevented by filling the ring-shaped hollows between the folds with a "Philite" body (indicated in fig.5 only in the case of the third unit). Each unit is now 40 cm long, and the total length of the tube, including the bulb-shaped shields at either end to prevent corona losses, amounts to only 2.40 m. In order to keep the primary electrons well together over the long distance between cathode K and

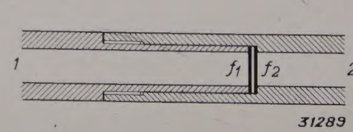

Fig. 6. The joining of the separate units. The ends of the anode tube of *1* and the cathode tube of *2* are provisionally sealed with thin metal foil, f_1 and f_2. The ends are soldered together and only a small quantity of air is enclosed between the foils. These air residues, as well as the gases freed in the perforation and smelting of the foils, are taken up by a getter.

[5]) A. Bouwers and J. H. van der Tuuk, Brit. J. Radiology **9**, 431, 1936.

target T a focussing electric field is applied near the cathode and at M a focussing magnetic field (by means of a ring-shaped permanent magnet). The losses of the electron current in passing through the two narrow connecting tubes amount to not more than a few per cent.

In each unit and in the complete device the principle of the subdivision of the voltage is applied. The middle sections (with partition) of the three units and the two connecting tubes reach such potentials that the voltage between cathode and target is divided into six equal steps. The simplest and best method of giving the separate parts of the tube the required potentials consists in tapping off the voltages in question from the high tension generator. This method can only be applied when a cascade generator is used which is designed especially for this type of X-ray tube in such a way that the number of stages in cascade arrangement corresponds to the desired voltage division along the X-ray tube. In general, however, tube and generator will not have been designed for each other; in that case the desired voltages must be tapped from a potentiometer. The carbon resistances which are used as potentiometer are oil-cooled. The same circulating oil also serves to cool the target. In the apparatus of *fig. 7*, where the

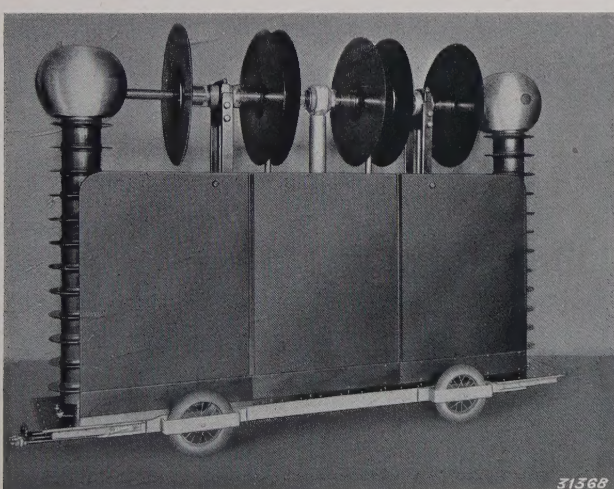

Fig. 7. Million volt X-ray tube mounted on a car. The total length, including the bulbs at each end for preventing corona losses, is 2.40 m. In the insulating columns at either side which support the tube oil-cooled potentiometer resistances are housed, from which the voltages are tapped for the different parts of the tube.

tube is mounted on a car, the resistances are housed in the two "Philite" columns at either side (200 megohms in each column) which support the anticorona bulbs of the electrodes. The middle of the tube is earthed in this case.

In each of the connecting sections between the three units a flexible metal middle piece has been mounted, in order to make it possible to transport the tube as a whole.

Use of the tube in an installation

In the practical application of the tube the surroundings must be sufficiently screened against the X-rays which are emitted in all directions by the target. As we shall see later, lead armour nearly 10 cm thick is necessary for this purpose. The method of construction shown in fig. 5, where the target is at the end of a long thin tube, makes this protection very easy. The lead jacket can be applied directly to this tube so that a relatively small amount of lead is sufficient. Several windows are left open in this lead jacket, so that if necessary several patients can be treated at the same time. An arrangement of the tube similar to the one chosen in the Cancer Institute in Amsterdam is shown in *fig. 8*. The high voltage of one million volts is supplied by a bipolar cascade generator, such as has already been described in this periodical [6]). The X-ray tube is mounted on top of the generator and its centre is earthed. The floor of the treatment room (above the generator) directly above the tube is vaulted; this is were the patients lie, separated by walls, when several are being irradiated at the same time. The distance of each patient from the target is at least 1 m, which is necessary as the target is at a high voltage (500 kV). The voltage across the tube is measured simply by the current which flows through the above-mentioned potentiometer resistance. This current is of the order of 1 to 2 mA. *Figs. 9* and *10* are two photographs of this installation which show other details of the method of mounting the X-ray tube.

If it is desired to bring the patient closer to the focus of the tube, the target may be earthed instead of the centre of the tube. In that case a high tension generator for one million volts with respect to earth is required. A projected installation of this type is sketched in *fig. 11*.

Properties of the X-radiation produced

The shortest wave length γ (in Å) of X-rays which can be obtained with a voltage V (in kilovolts) follows from the relation

$$V\gamma = 12.4$$

At $V = 1000$ kV the limit of the X-ray spectrum thus lies at $\lambda = 0.0124$ Å. In *fig. 12* the spectrum is given of the radiation of a million volt tube,

[6]) Philips techn. Rev. **1**, 6, 1936; **2**, 161, 1937.

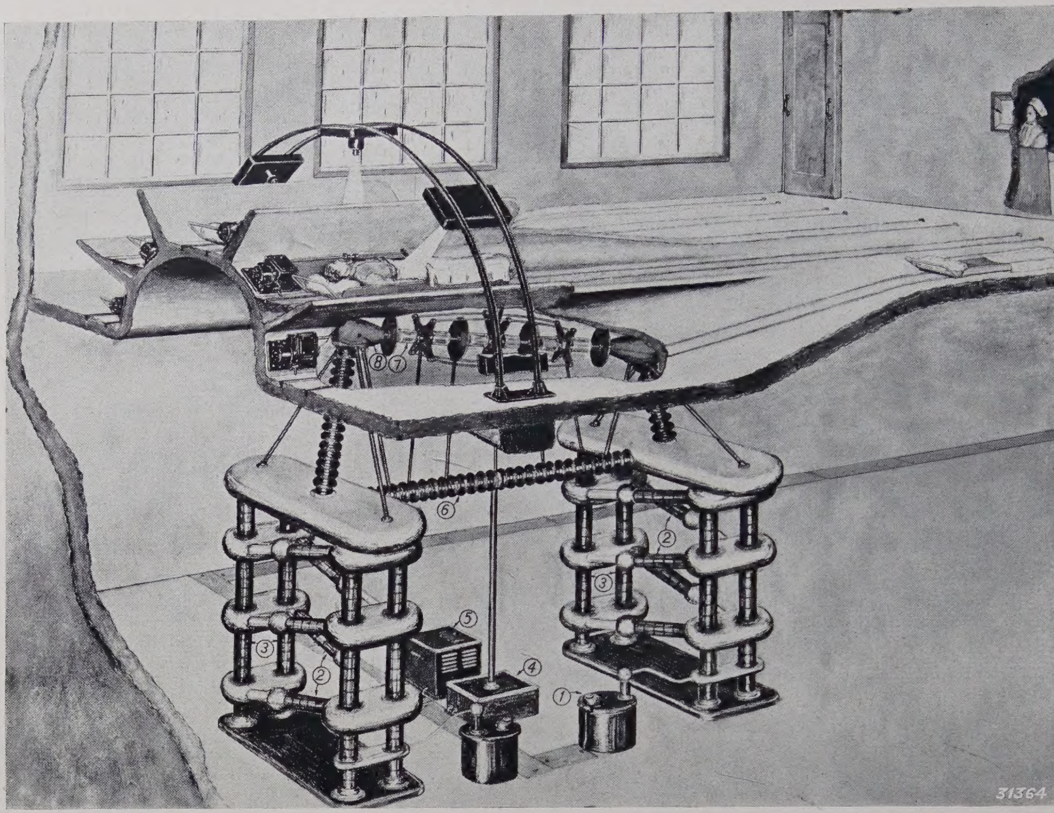

Fig. 8. Sketch of the complete therapy installation (the installation in the Cancer Institute in Amsterdam is carried out on this principle). The tube is mounted on the top of a cascade generator. Above the tube is the treatment room where several patients (in Amsterdam three) can be treated at the same time, *1* high tension transformers, *2* valves, *3* condensers, *4* oil container with pump for cooling the potentiometer resistances *6* and the target, *5* generator for the high frequency heating of the cathodes of the valves, *7* X-ray tube, *8* holes for the passage of the effective beams of radiation through the lead jacket around the target. The patient is placed by means of a beam of light so directed that it coincides with the X-ray beam at the surface to be irradiated.

and also the line spectrum of the γ-radiation of radium. The maximum of the radiation of the tubes lies at about 0.018 Å, but at the same time a large amount of softer radiation is emitted. The maximum of the emission can be shifted toward shorter wave lengths by allowing it to pass through a suitable filter. The soft radiation is hereby absorbed to a greater extent than the hard, so that the radiation becomes harder after passing through the filter. The effect of filters consisting of plates of lead 1 and 2 mm thick respectively is shown in fig. 12.

The hardness, *i.e.* the penetration capacity of an X-radiation, is practically always indicated by the thickness of some material or other (usually copper) by which the dose is reduced by one half. In *table I* these half value layers are indicated as measured at different voltages for different filters. It may be seen that at 800 kV a suitable filter should be more than 5 times as thick as at 200 kV. For the practical application of the radiation in therapy this means that the radiation can penetrate more easily to the focus of the disease inside

Table I

Half value layers for X-rays, obtained with different voltages and different filters. The percentage depth dose at 10 cm depth is the ratio d_{10}/d_0, the back scattering the ratio $(d\text{-}d_0)/d$, the residual radiation the ratio d_{20}/d_0, where d_0 is the dose measured on the surface of the skin, d the dose at the surface of the skin when the object is removed, d_{10} the dose at a depth of 10 cm under the skin and d_{20} the dose at the foreside of the object. The measurements were carried out with a water phantom 20 cm thick, of which a field of 150 sq.cm of the fore side was irradiated at a distance of 100 cm from the focus.

Voltage in kV_{max}	Filter thicknesses of metal in mm	Half value layer in mm Cu	Percentage depth dose in %	Back scattering in %	Residual radiation in %
200	1 Cu	1.6	41.0	29.5	7.4
400	0.5 Sn + 3.5 Cu	4.4	44.5	16.5	10.4
600*	0.5 Sn + 3.5 Cu	5.5	45.0	13.8	11.3
800*	0.5 Sn + 3.5 Cu	5.9	45.5	12.3	12.0
800*	3Sb+0.5Sn + 3.5Cu	8.7	47.0	9.0	—

*) These voltages had a ripple of about 20%, while the others were constant direct voltages.

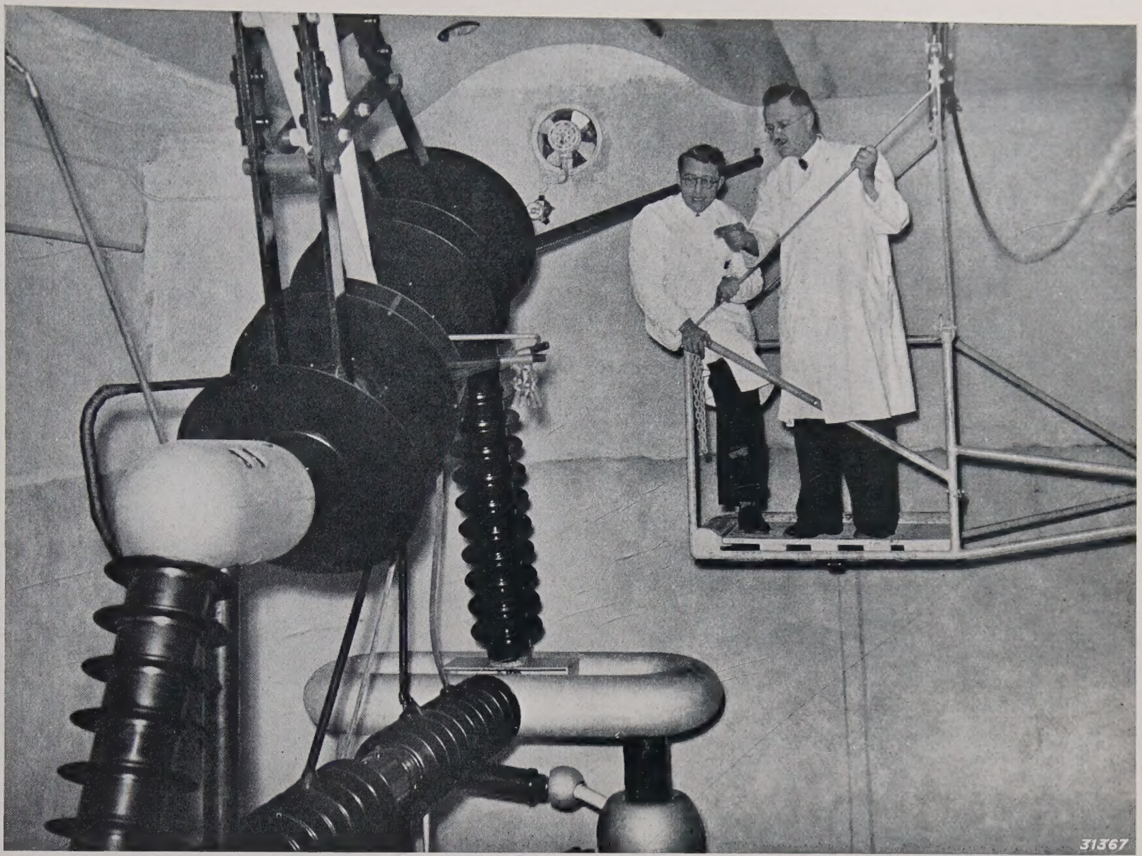

Fig. 9. Actual installation as sketched in fig. 8 in the Cancer Institute in Amsterdam.

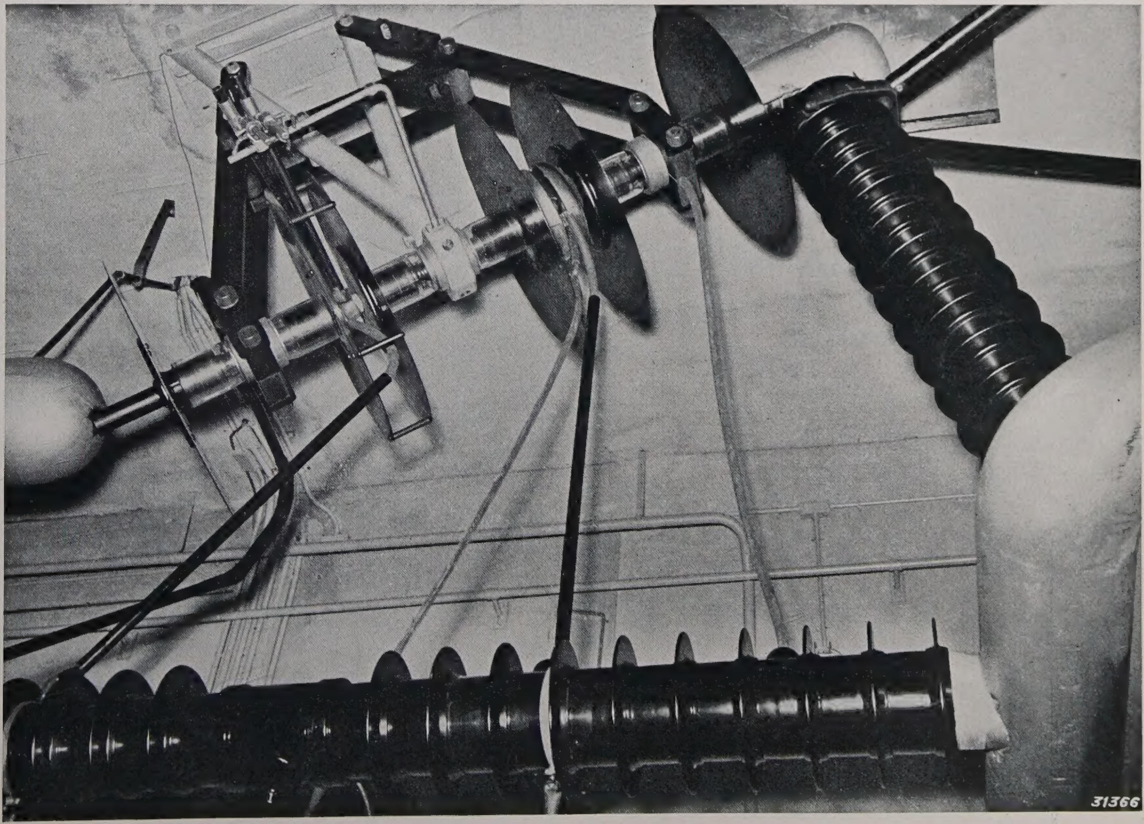

Fig. 10. Mounting of the X-ray tube in the installation of the Cancer-Institute. The centre of the tube is earthed and is suspended from the ceiling. The first and third units are borne by supports of insulating material. The different taps from the potentiometer resistances can be clearly seen.

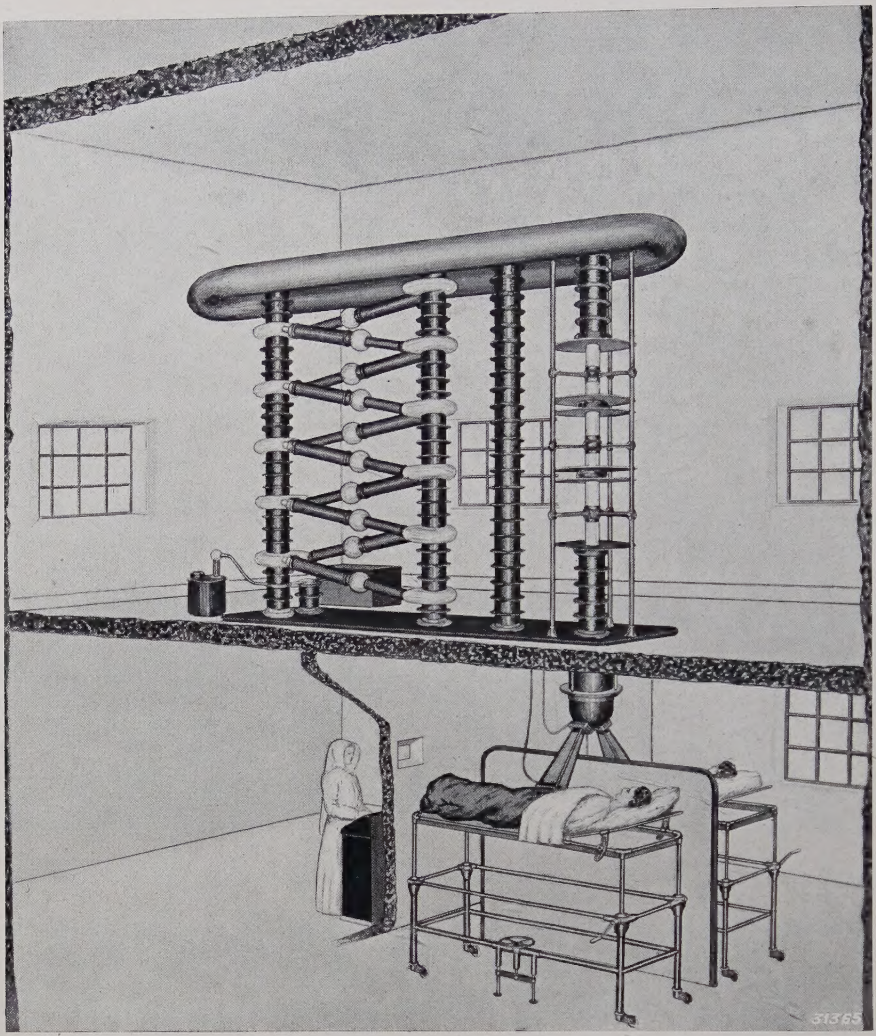

Fig. 11. Projected installation with an X-ray tube for one million volts, in which the source of rays (the target) is earthed. The cascade generator must in this case give a voltage of one million volts with respect to earth and is therefore of the single pole type.

the patient's body. The degree of this penetration is expressed by the above-mentioned percentage

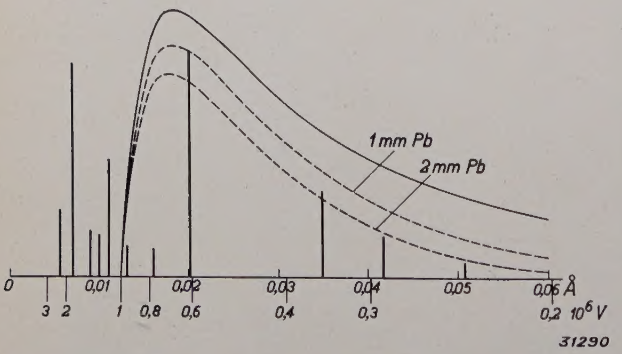

Fig. 12. The line spectrum of the γ-rays of radium and the spectrum (I) of the X-radiation of a million volt tube (according to Eve and Grimmett, Nature **139**, 52, 1937). The maximum of the X-ray spectrum may be shifted toward shorter wave lengths by means of filters, as is shown from the dotted curves recorded upon the use of filters of 1 and 2 mm of lead respectively. In addition to the wave lengths along the abscissa, the minimum voltages are given in 10^6 volts, which are necessary for the excitation of X-rays of the corresponding wave length.

depth dose. Table 1 gives the percentage depth dose measured on a water phantom [7]) at different voltages. The improvement obtained from 41 per cent to 47 per cent may be very important practically. In the same table the percentage back scattering is also given, *i.e.* the increase of the dose at the surface of the skin caused by the presence of the object irradiated. Back scattering, as the table shows, decreases rapidly with increasing hardness of the rays. It may in general be said that a beam of hard rays keeps its geometric form better in passing through the object than soft rays, since the hard rays are scattered less. The healthy tissues surrounding the lesion are therefore less exposed to hard rays.

[7]) In order to study the absorption and scattering of X-rays in the human body, use is made of devices, which show the same behaviour in the processes mentioned. Such phantoms are often made of water, sometimes also of "Philite", paraffine and similar substances. See for example Philips techn. Rev. 4, 120-121, 1939.

Another important point is the rapid increase of the dose obtained. At 870 kV and 1 mA the tube described already yields the same dose as 1 kilogram of radium. This is important not only because of the possibility of shortening the times of irradiation, but also because the distance from the focus to the skin may be increased, whereby a larger percentage depth dose is attained [8]). In *table II* the doses

Table II

Free-in-air dose at different voltages (constant direct voltage) and 1 mA tube current, measured at a distance of 1 m from the focus (perpendicular to the direction of the primary electrons) with a filter of 2.5 mm of copper. The thicknesses of lead also given are required to reduce this radiation to the tolerance dose (10^{-5}/sec).

Voltage in kV	Dosage in r/min.	Thickness of lead for protection in mm
200	0.45	3.5
400	3.5	18
600	8.1	38
800	14.0	62
1000	20.0	88

are given which were obtained under otherwise similar conditions when the above described tube was operated at different voltages. From 200 to 1 000 kV the dose becomes 45 times as great with the same current. The efficiency thus increases by a factor 9. Considering this result and also the great reliability of X-ray installations for higher voltages work, it may be asked whether the application of higher voltages for obtaining the same dose is not preferable for economic reasons alone over the use of tubes with voltages of around 200 kV and high currents. In this respect, however, the costs of acquisition also play a part.

Protection against the radiation

We have already mentioned incidentally the necessity of an efficient protection against the rays. The radiation outside the effective beams of rays must be reduced to the so-called tolerance dose [9]) of 10^{-5} r/sec. In table II, next to the effective dosages obtained, the thicknesses of lead required for this protection are indicated. It may be seen that at the highest voltage a lead plate 9 cm thick is necessary. A kind of lead bulb having this thickness of wall is placed around the target.

In addition to the primary radiation outside the effective beams, the radiation in the effective beams which remains after passing through the patient must also be absorbed. This residual radiation forms a fairly large percentage of the primary radiation (see table I), so that thicknesses of lead of up to 7.5 cm are necessary. The secondary X-rays, on the other hand, which originate in the irradiated body and are emitted in all directions, are relatively soft and can be rendered harmless by quite thin lead plates. This is very fortunate when working with hard rays since the walls of the treatment rooms need not be too heavy. In the irradiation of a field of 150 sq.cm of the phantom at a distance of 100 cm from the focus, with a tube voltage of 800 kV, 1 mA tube current and 2.5 mm of copper as filter, 2 mm of lead were found sufficient to reduce the scattered rays at a distance of 1 m to below the tolerance dose.

[8]) In the passage of the rays through a body the dose decreases, in addition to the decrease by absorption, with the square of the distance from the focus. The further the irradiated object is from the focus, the smaller the influence of this decrease.

[9]) In the article cited in footnote [7]) the tolerance dosage is given as 0.2 r/day. The day is considered to consist of 8 working hours.

A NEW PRINCIPLE OF CONSTRUCTION FOR RADIO VALVES

621.385

A radio valve is described in which the pinch type of lead-in of the connection wires is replaced by a horizontal flat base of pressed glass. In this construction the distance between the leads is greater than in the pinch type, the lengths of the leads in the glass and the lengths from the points of contact outside the valve to the electrodes inside the valve are much shorter. Moreover the construction is much stronger, while it was also possible to lead out the grid connection at the bottom while still retaining the desired value of the capacity between grid and anode. The advantages resulting from these changes are discussed. They are manifested especially clearly when the valve is operated on very short wave lengths. This is due partially to the fact that the cap of insulation material which is ordinarily used may be dispensed with.

Introduction

Consideration of the gradual development of many kinds of new technical products shows that a structural form was at first almost always chosen which had previously served other similar purposes. The first automobile resembled an old-fashioned carriage, the razor, before the transition to safety razors, resembled an ordinary knife, and the oldest electric switch resembled a gas tap.

In the same way the earlier radio valves are similar in many structural details to the electric lamp. As in the case of electric lamps an evacuated glass bulb was necessary in order to raise a wire to a high temperature and maintain it at that temperature without its being attacked. The method of pumping and the leading in of the electrical connections through the wall of the bulb were taken over practically unaltered. Evacuation was through a small glass tube, the exhaust tube, which was originally fused to the top of the bulb. A few wires, with the same coefficient of expansion as the glass which was squeezed around them after heating, served for leads through the pinch. In the same way as with an electric lamp, a cap was cemented to the bulb in order to facilitate connection in radio sets.

The technical requirements which should be met by radio valves were at first not sharply defined, and were indeed still partly unknown. During the steady progress of development, however, a continually better insight was obtained into the specific requirements of radio valves and into the extent to which these requirements were restricted by the prevailing construction of the valves.

What are the requirements which must be satisfied in the construction of a radio valve?

We shall begin by discussing several of these requirements in some detail. It was soon discovered that the mutual insulation of the electrodes, cathode, grid and anode, must satisfy very high standards. In the pinch construction taken over from the manufacture of electric lamps, however, these electrode connections lie close together (from 0.5 to 1 mm apart). The heating up of the pinch during operation of a radio valve therefore sometimes led to electrolysis of the glass, to leakage and breaking of the valve. With the introduction of valves with several grids, such as pentodes, and especially later on in the development of octodes and other mixing valves, the number of leads through a single pinch was increased very much. Since the insulation must be very high, especially between cathode and control grid, and the capacity C_{ag} between anode and control grid must be very low in order to avoid coupling between anode and grid circuits, the lead of the control grid was transferred to the top of the valve. This precaution answered the purpose very well, but for the use of the valves

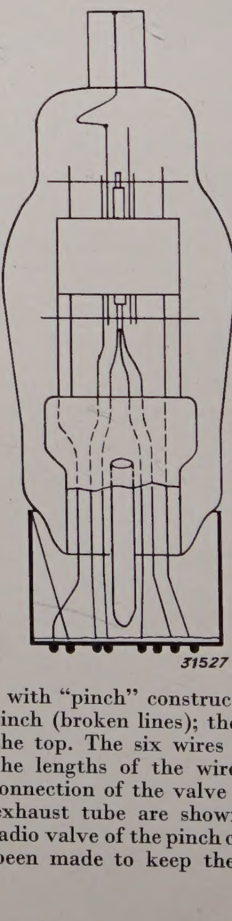

Fig. 1. Radio valve with "pinch" construction. Six wires pass through the glass pinch (broken lines); the connection for the control grid is at the top. The six wires are parallel over a great length and the lengths of the wires in the glass are considerable. The connection of the valve to the cap and the protection of the exhaust tube are shown in the figure. In this recent type of radio valve of the pinch construction already much effort has been made to keep the dimensions small.

in a radio set it would have been preferable to bring out all the leads at the same end of the valve.

The use of shorter and shorter wave lengths makes it essential to keep all the capacities between the different electrodes, the self-inductions of the different leads and their mutual inductions as low as possible. With the pinch type of construction a limit is soon reached, since the leading-in wires, run parallel and close to each other in the pinch and pinch tube for some little distance, have quite high capacities and self-inductions. In the pinch these wires are separated by glass with a fairly large dielectric constant which further increases the capacities. The width of the pinch is being continually increased (see *fig. 1*), but since the leads in such a pinch lie in a single plane, and the pinch must not touch the walls of the bulb and must be able to pass through the neck of the bulb, the distance between the outermost wires in the pinch is usually not much more than half the diameter of the neck of the bulb.

It is, however, not only desirable that the capacities between the electrodes of a valve should be small, but they must also be as constant as possible. Upon switching on a radio set, the temperature of the valves increases gradually. The capacities between the electrodes therefore will only be sufficiently constant when the temperature coefficient of the dielectrics in the valve is low. This condition is fairly well satisfied by the glass of the pinch, it is much less nearly satisfied by the press material of the cap. The result is that the resonance frequencies of the two tuned circuits change to a certain extent after switching on. Furthermore it is desirable to have the value of the capacities equal in different valves of the same type, so that the set need not be readjusted when a valve is changed.

The position of the wires in one plane parallel to the flat part of the pinch is capable of being improved upon from the mechanical point of view also. The inside assembly of the radio valve, *i.e.* the grids and the anode, is mounted on the pinch by welding, and the strength of such a construction is too low for shocks perpendicular to the plane of the pinch. The inside assembly of the valve is therefore often supported against the upper part of the tube wall by mica plates.

These and similar considerations have led to the search for a different type of construction from the traditional one. We shall discuss in this article a new type of glass construction worked out by Philips, and the results achieved with it.

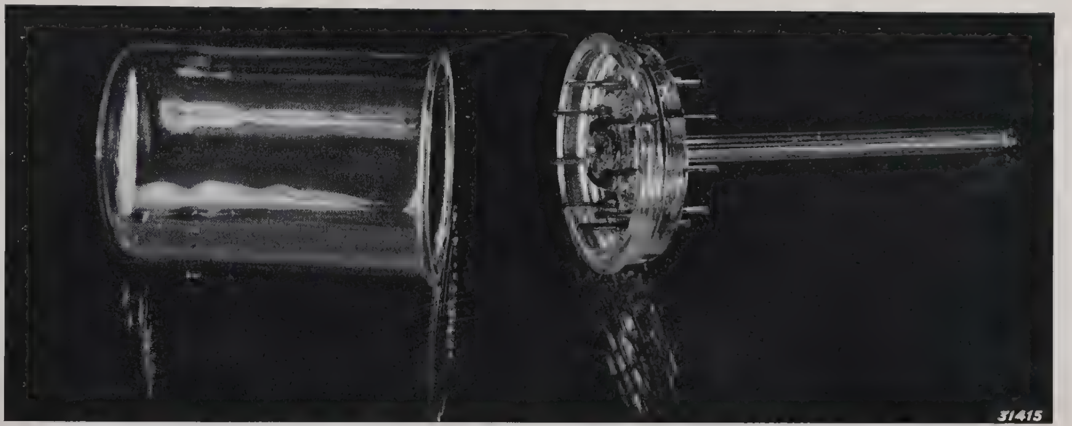

Fig. 2. Photograph of the bulb and the circular base of moulded glass which are fused together along the flange. At the centre of the base is a depression where the exhaust tube is fused on. The chrome iron pins pressed into the glass are clearly visible. Contact is made in the socket through the projecting ends of these pins. The inside assembly is mounted in the valve on these pins (see Fig. 4).

Construction

In the new type of construction the valve consists mainly of a circular glass base upon which the inside assembly is mounted and a glass cylinder which is fused to this base along a flange. These two parts are shown in *fig. 2. The base plate is completely moulded out of glass.* This pressing of the glass can easily be done mechanically. During the process of moulding the base plate the chrome iron leads can be included in the mould and the joint between glass and leads is airtight. It was found possible to choose the leads thick enough to serve directly as contact points without danger of leakage or breakage of the glass. The construction of the socket must of course for good contact be adapted to the diameter of the pressed-in chrome iron contact pins.

The chrome iron pins are placed in the moulding in a circle with a fairly large diameter (21 mm). The distance between them is therefore great (with 9 pins it is 7 mm) and very good insulation is thus guaranteed. At the centre of the base there is a depression in which a stem is fused (*fig. 3*). Be-

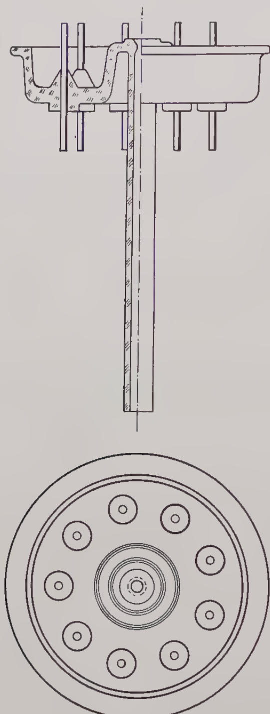

Fig. 3. Drawing showing the details of the circular pressed glass base with exhaust tube and leading-in wires of chrome iron. There is a depression in the base for attaching the exhaust tube. The length of the wires in the glass is considerably less than in the case of the pinch.

cause of this depression the length of the stem to the point of sealing off, even when the distance from the sealing off point to the base is short, is not so small that the glass will break at the joint between base and stem upon sealing off.

The inside assembly of the valve is strongly mounted on the leading-in pins (*fig. 4*), its base is broad and there is plenty of room between the different wires. All the connections including that of the modulation grid are led out at the bottom. The shortening of the length of the connections from the base to the electrodes in this type of construction is shown in *fig. 5*.

The very small value of the anode-grid capacity C_{ag}, which is necessary to prevent a capacitative coupling between the anode and grid circuits, is obtained by choosing for the grid and anode connections two lead-in pins which are far enough apart. In addition some of the electrodes are screened from each other by vertical shields placed inside the tube on the base. Several separate sectors are thus formed through which different wires are led in without their being able to influence each other. In the photograph (fig. 4) these can be seen quite easily. The shielding is finally completed by a metal cap which is described below.

After assembly the glass cylinder is placed over the electrodes and fused to the base along the flange. The evacuation of the valve, the outgassing of the metal parts and the improvement of the vacuum by the evaporation of a getter is carried out in the usual way. After the stem is sealed off the valve is practically complete, but must still be finished off. A cemented cap of moulded material with contact pins is unnecessary, since the chrome iron pins may serve as contacts. Some protection is, however, necessary for the sealed-off exhaust tube which might easily be broken by a knock. A flat metal shield is therefore fastened to the underside of the valve. All the connections project through holes in this shield and can make contact in the socket. At the centre of the shield is a metal

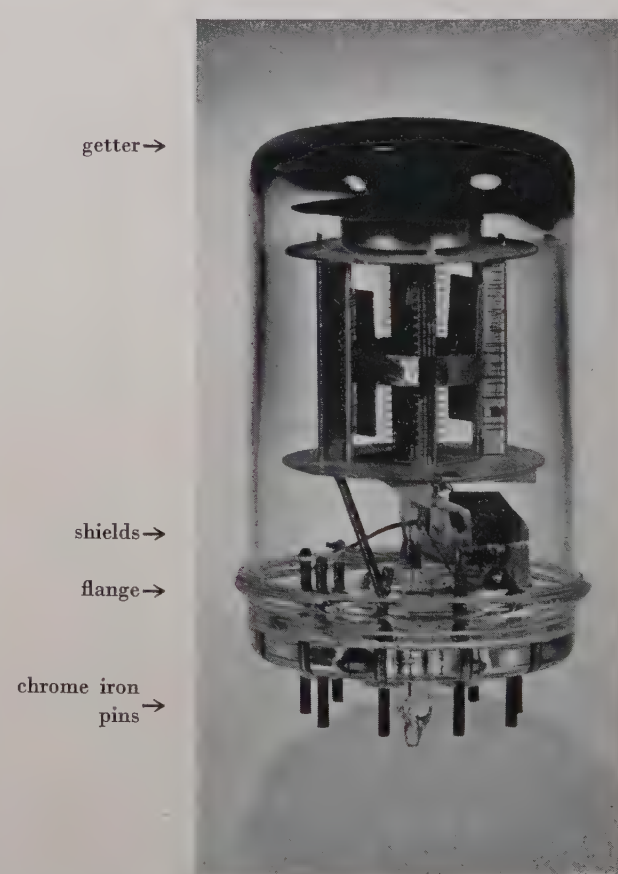

Fig. 4. Photograph of the exhausted and sealed-off valve. Directly above the flange along which the base and bulb are fused together may be seen the two mutually perpendicular shields which separate grid and anode leads from each other, making it possible to keep the grid-anode capacity C_{ag} low. The length from the sealing-off point of the exhaust tube to the base is short. The getter is deposited at the black spot in the upper part of the bulb.

tube which protects the exhaust tube (*fig. 6*). This metal tube fulfils another purpose at the same time. In inserting the radio valve in a suitable socket in which the pins make contact, there is only one permissible relative position of valve and socket. In order to find this position the shielding tube is provided with a pointed cam which fits into a slit in the socket. When the tube is pressed far enough into the socket the cam locks. This can be done in two ways. After the valve is pressed down in the socket it is turned slightly: the upper edge of the cam is then held against the lower side of the bottom of the socket so that the valve cannot be pulled out. During this turning the contact pins in the bottom are pressed in the springs of the socket and good contact is obtained. The ring-shaped groove at the end of the metal tube may also be used to lock the valve; it must then be caught by an appropriate fastening in the socket.

The shielding of the inside assembly of the valve against inductive or capacitative interferences from the outside can be accomplished in different ways. We shall not go into that here, however, but call attention to the fact that the metal shield provided sufficient protection at the lower side.

Properties of the valve

We shall deal one at the time with the results obtained with valves of this construction.

Temperatures of the glass at the sealing-in points

In the pinch type of construction the pinch reaches temperatures which in unfavourable cases may amount to 200 °C or even higher. The new construction reduces the temperature at the sealing-in points to 90° C. Since the conductivity of the glass varies exponentially with the temperature, this reduction results in better insulation and less chance of electrolysis of the glass. The probability of breakage of the glass is also reduced.

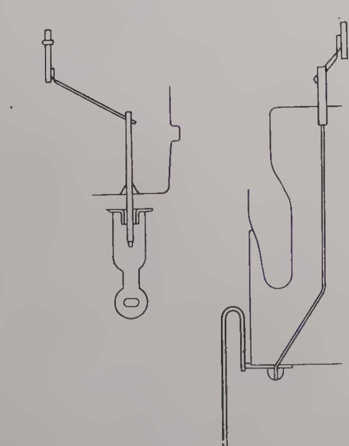
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Fig. 5. Detail drawing of the length of the connection wire from the cathode to the contact strip of the valve socket in the new design (left) and in the pinch construction (right).

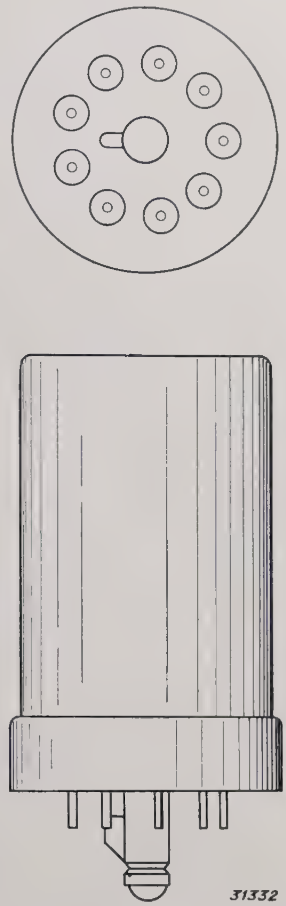
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Fig. 6. Drawing of the finished valve with protecting tube and pointed cam.

Change of the capacities between the electrodes due to changes in temperature

The capacity between two contact pins in a radio valve cap of the old construction is about 0.3 $\mu\mu$F. During heating up the increase in temperature of the cap is about 10° C. Since the temperature coefficient of the dielectric constant of the artificial resins is about 50×10^{-4} per degree, the capacity changes by 0.015 $\mu\mu$F. This change in capacity gives in a circuit oscillating on a wave length of 13 m and with a tuning capacity of 50 $\mu\mu$F a change in frequency of 3.4 kilocycles. Even greater than this is the change of capacity between leading-in wires in a glass pinch during the warming up. The temperature coefficient of the dielectric constant of glass is 5×10^{-4} per degree, thus lower than for artificial resins. The increase in temperature is here, however, greater, as we have seen, namely 150 °C. The capacity between the leads is 1 to 1.5 $\mu\mu$F in the cold state, and the change due to heating

may amount to 0.09 μμF. As a result of this a change in frequency of 20 kilocyles may occur under the same conditions as above, and the reception is appreciably disturbed.

Under these circumstances the omission of the cap and the maintenance of a low temperature of sealing-in points, such as are possible with the new construction are a great advantage. It was found that in the new design on a wave length of 20 m and with a tuning capacity of 75 μμF with a room temperature of 25 °C the frequency change did not exceed 2.7 kilocycles, while with the same tube with the pinch type of lead-in connection wires it amounts to 4.4 kilocycles.

Tolerances in the capacities

When a defective radio valve is replaced by a new one, the new valve must have the same capacities between the different electrodes. The set is adjusted by means of trimmers to an average capacity, and the actual values of the capacities in different radio valves of the same type must therefore have only slight tolerances. In radio valves with the pinch construction these tolerances for the different capacities, with the exception of that between anode and control grid which has a much smaller value, had a value of about 0.6 μμF. In the new construction on the other hand the value is only about 0.2 μμF.

Capacity between control grid and anode

In screen grid valves, in order to avoid reaction of the anode circuit on the grid circuit, the capacity between anode and control grid must be very small. Therefore, as already mentioned, the grid connection is led out at the top of the valve in many types, and the grid and anode circuits are screened from each other inside the valve. In this way it is possible to reduce the capacity to 0.002 μμF. This point necessitated much care in the new construction, since the anode and grid connections are now led out on the same side, they both pass through the base. By the precautions discussed it was also found possible in the all-glass construction described to reach values of from 0.002 to 0.003 μμF or even less if necessary.

Properties for operation on short wavelengths

Due to the shortening of the leading-in wires and the greater distances between them, it was to be expected that for operation on very short wavelengths, 5 m for example, the all-glass valve would prove more satisfactory than that with the pinch construction. The input as well as the output resistances of the new construction were actually found to have values which give the all-glass valve advantages over valves with pinch construction for operation on very short wavelengths.

The following table illustrates the difference. Since the input resistance of a valve of the earlier form of construction was always five to ten times as small as the output resistance, the value of the input resistance restricted the value which could be chosen for the impedance of the coupling circuit between two valves. In the table values of the input resistance in the cold state and in the working state are given for two wavelengths, three and ten meters, for the same type, EF 9, in the old and new form of construction. In the old form the valve was provided with a P-cap (see fig. 1).

Table

Wave length	Cold resistance (10^3 ohms)		Working resistance (10^3 ohms)	
	old	new	old	new
3 m	36	28	2	4
10 m	460	360	27	66

When in operation, *i.e.* when the valve is warm, the input resistance of the new type of construction is thus more than twice as great as in the old construction. The impedance of the coupling circuit between two valves may therefore be increased, and a greater gain per stage of amplification is possible.

It may be seen from the values given that the differences become smaller at longer wavelengths. In many respects, however, the other advantages mentioned are still of importance.

Compiled by P. G. CATH.

SYNTHETIC SOUND

by J. F. SCHOUTEN.

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An apparatus is described with which synthetic sound can be produced, *i.e.* sounds with prescribed periodic wave forms. The characteristics of the apparatus are dealt with in detail. The apparatus has been employed for the investigation of different physiological acoustical problems, such as the influence of phase on sound perception and non-linear distortion in the ear.

In an earlier number of this periodical [1]) we described a method by which a sound recorded on a strip of film was immediately analyzed into its different sinusoidal components. We shall now describe a method whereby the reverse is done, *i.e.* a sound of prescribed character of periodic vibration, or in other words a sound consisting of sinusoidal components of prescribed amplitude and phase, is obtained synthetically. This method permits a closer study of a number of problems which are connected with the nature of the perception of sound.

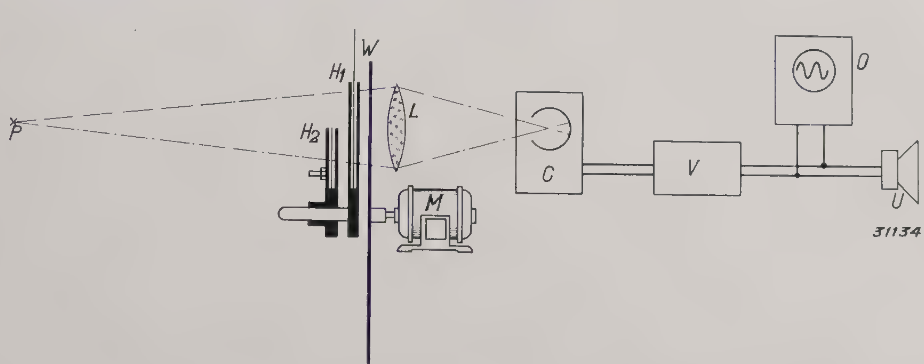

Fig. 1. Apparatus for producing synthetic sound. The wave form cut out as a stencil is placed in the holder H_1 and homogeneously illuminated by the point source of light P. The motor M drives the disc W, which is provided with slits. The light transmitted trough the slits is focussed by lens L on the photo electric cell C. The photocurrents are transformed into sound *via* the amplifier V and a loud speaker U. The wave form is checked by means of the cathode ray oscillograph O. For special experiments a second holder H_2 is introduced in front of H_1. This second holder is for a second stencil, and may be rotated with respect to H_1.

Apparatus for the production of synthetic sound

The apparatus is based on the principle of the intensity of a light flux as a function of time being made to vary proportionally to the desired wave form. The light flux is incident on a photo electric cell and finally transformed into sound *via* an amplifier and a loud speaker. The principle is realized in the following way [2]). The desired wave form is cut out of paper so that it can be inserted in the holder H_1 (*figs. 1* and *2*). This paper stencil is homogeneously illuminated by a point source of light (a tungsten arc lamp) at a great distance. Behind the holder H_1 there is a rotating aluminium disc in which 9 slits have been made, each with a width of 1 mm and at distances of 40° from each other. Behind the disc, which is driven by a motor, is a lens which focusses the light source upon the photo electric cell. The only light which can fall upon the photo electric cell is that which has passed through the part of the stencil cut away and one of the slits. When the disc is turning, the amount of light transmitted at each moment is proportional to the height of the part cut away at the point behind which there is a slit at that moment. In consequence of the method of scanning the desired wave form must be traced in polar coordinates. The centre of this system of coordinates must be situated on the extension of the axle of the motor. Only one period of the vibration is drawn in such a way that the period occupies exactly the distance between two slits, *i.e.* 40 degrees, when the disc is turning and one of the slits has traversed the stencil, the following slit is just ready to begin at the other side.

Since with this arrangement negative values of the light transmissibility cannot be produced, a constant quantity is added to all the coordinates of the wave form to be reproduced, which quantity is equal to the largest negative value occurring. In the case of a purely sinusoidal vibration the height of the portion cut away is not $a \cos \varphi$, but *e.g.* $a - a \cos \varphi$ (*fig. 3*).

The frequency can be determined by regulating

[1]) J. F. Schouten, Philips tech. Rev. 3, 298. 1938.

[2]) J. F. Schouten, Proc. Kon. Ned. Ak. Wet. 41, 1086, 1938.

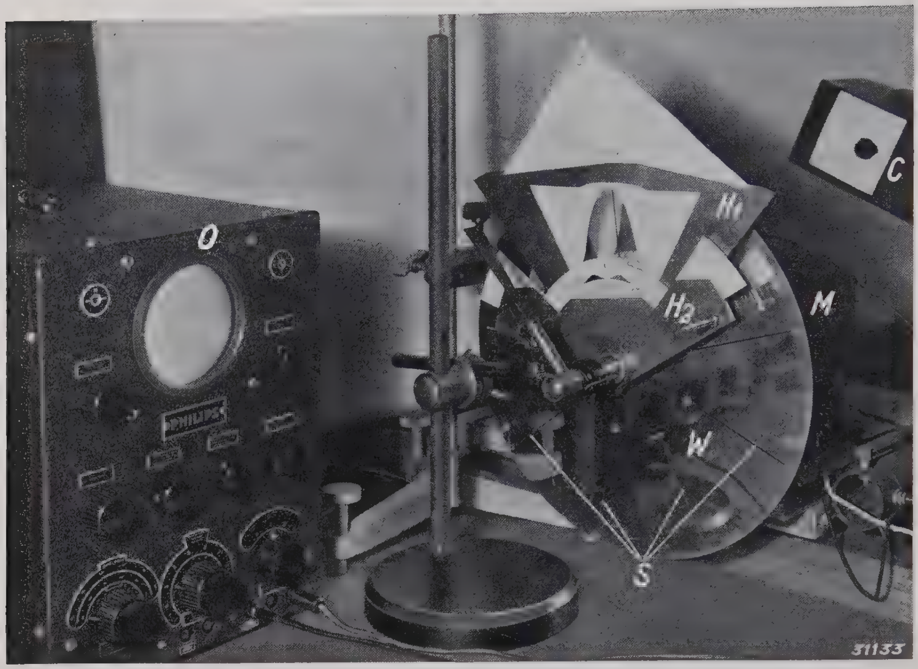

Fig. 2. Photograph of the apparatus. S are the slits in the disc W. In holders H_1 and H_2 the stencils of two different sinusoidal vibrations have been placed.

the number of revolutions per minute of the motor. This number of revolutions was usually $22^2/_9$ per sec and a fundamental tone of $9 \cdot 22^1/_2 = 200$ c/s was thus obtained.

If the desired form is given as the sum of a number of sinusoidal components, the components may be added and the resultant wave form cut out. Often, however, it is an advantage to cut out the forms separately one above the other. If it is desired to be able to change the relative phase of the components during the experiment, the components are cut out in separated models. To this end a second smaller holder H_2 is introduced in front of H_1 (see figs. 1 and 2) which can be turned about an axis in the extension of the motor axle. Altogether a region lying between radii of 65 and 130 mm in the polar coordinate system is available for the stencil cutting.

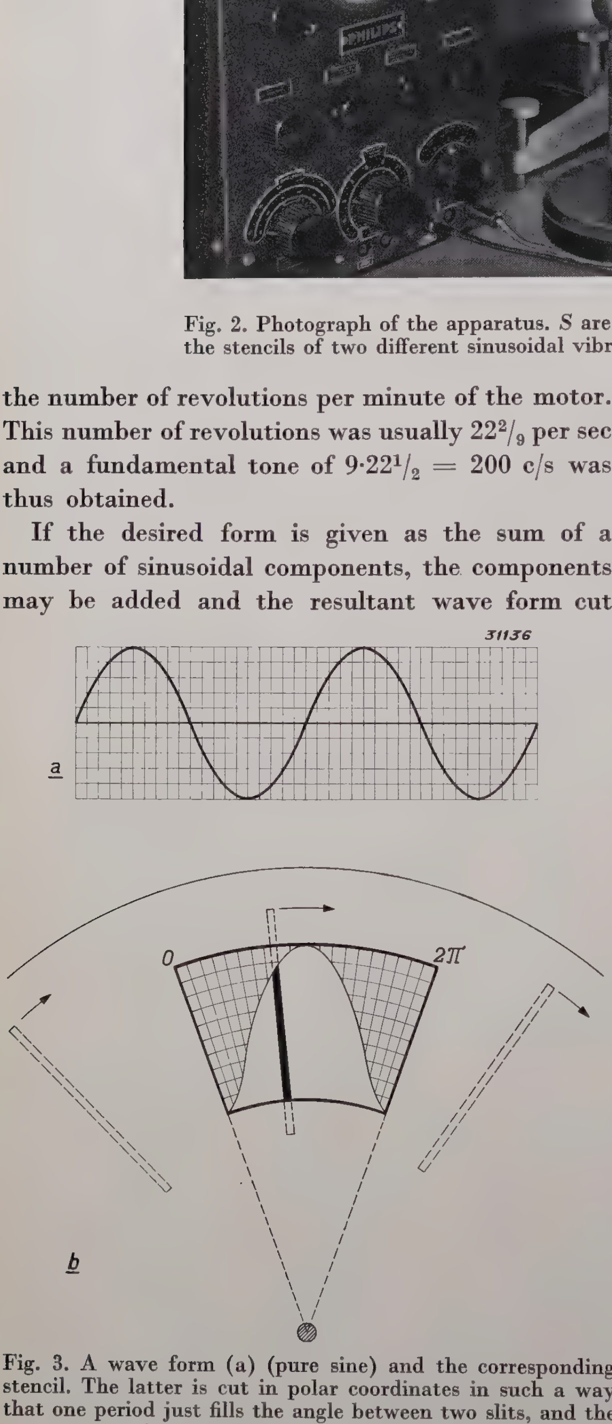

Fig. 3. A wave form (a) (pure sine) and the corresponding stencil. The latter is cut in polar coordinates in such a way that one period just fills the angle between two slits, and the greatest negative ordinate of the wave form corresponds to zero light transmission.

One very attractive property of the apparatus here described is that it makes it possible to study directly the influence exerted on sound perception by changes in the wave form. For example, when several components have been cut out one above the other, any one of these components can be made to disappear, simply by screening this part of the stencil from the light. Furthermore in the same way by partial screening a sinusoidal wave form can be flattened or provided with sharp indentations, and the effect of this can be heard in the sound produced.

Influence of the finite width of the slits

To what extent is the obtained displacement of the particles of air as a function of time a faithful image of the stencilled wave form? The most serious source of error of the apparatus is the finite width of the slits in the rotating disc. It is clear that this error will consist in the fact that the fine structure in the wave form of the

order of the width of the slit is not brought out; the apparatus, in optical terminology, possesses a limited resolving power. What does this mean from the acoustic point of view? If the stencil only has the n_{th} harmonic, with an amplitude a, the amount of light transmitted would be proportional to the ordinate

$$a - a \cos n\varphi, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (1)$$

where the variable φ varies from 0 to 2π during the traverse of one slit. In the case of a slit which occupies a sector of the finite angle $\Delta\varphi = \Theta$, *the higher harmonics in gradually diminishing intensity.*

In *fig. 4* the variation of the function (3) is reproduced. The factor f_n equals 1 for $n = 0$, for higher values of n it falls gradually and becomes zero when n reaches the values $2\pi/\Theta$. This can also be immediately appreciated physically. The period of the n^{th} harmonic has the value $2\pi/n$. If this length is exactly equal to the width of the slit, the average value of the transmission is exactly zero, and this harmonic is therefore not passed

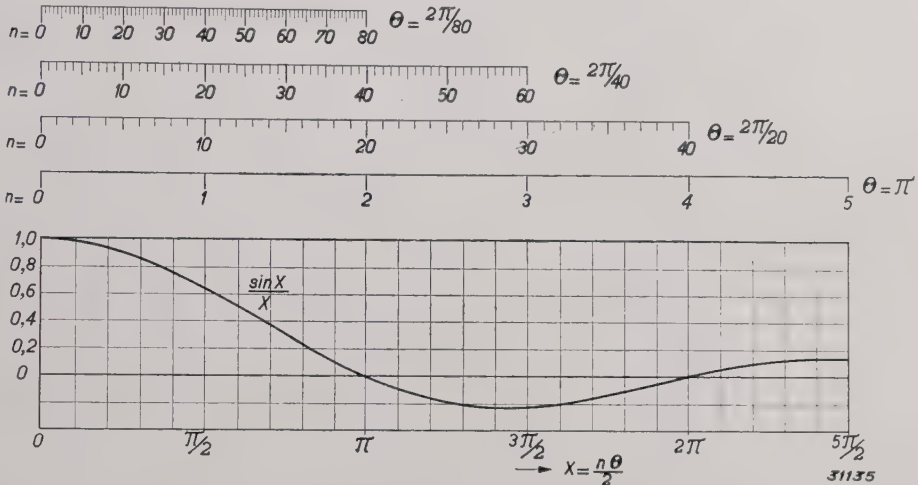

Fig. 4. Variation of the function $sinx/x$ with the abscissa $x = n/\Theta 2$. This function gives the "frequency characteristic" of the disc. In practice only the first part $(0 < x < \pi)$ is used. From the accompanying n scales it may be seen that more harmonics can be rendered with fairly exact intensity, the smaller Θ (the width of the slit).

the amount of light transmitted is, however, proportional to the average value of the ordinate in this sector; this is:

$$\frac{1}{\Theta}\int_{\varphi-\frac{\Theta}{2}}^{\varphi+\frac{\Theta}{2}} (a - a\cos n\varphi)\,\mathrm{d}\varphi = $$
$$= a - \frac{2a}{n\Theta}\sin\frac{n\Theta}{2}\cos n\varphi \; . \; . \qquad (2)$$

From this it may be seen that the n^{th} harmonic is not reproduced with its true amplitude, but with an amplitude $f_n \cdot a$ when

$$f_n = \frac{\sin\dfrac{n\Theta}{2}}{\dfrac{n\Theta}{2}} \quad . \quad . \quad . \quad . \quad . \quad . \qquad (3)$$

It is easy to understand that the factor f_n is not affected by the presence or absence of other harmonics on the stencil. Each harmonic is therefore reproduced with a characteristic attenuation. *The finite width of the slits has the same effect as an electric filter preceding the amplifier which passes* by the disc. For higher values of n the function f_n varies in an oscillating manner; for practical purposes, however, only the first part of the curve is important.

The factors f_n have another special significance. They are equal to the components of the development of the transmission of the disc in a Fourier series. Plotted as a function of the angle, this transmission represents a periodic impulse in which the ratio of the width of the impulses to the mutual separation is equal to $\Theta/2\pi$. The Fourier coefficients of these functions are just given by formula (3).

The fact that ideal reproduction is attained with an infinitesimally narrow slit must be understood in this connection in the following way: the factors f_n in that case, see formula (3), all become equal to unity: the Fourier spectrum of a periodic, repeated, infinitesimally narrow impulse contains all the harmonics in equal intensity [3]).

Another extreme case occurs for example when the width of the slits is made equal to that of the intervening space ($\Theta = \pi$, the "square sine"). The factors then become zero for all even values of n. No matter what the form of the stencil, only the odd harmonics will be able to occur in the sound obtained.

The factors f_n, which have been derived theoretically above, can also be determined experimentally

[3]) See for example page 307 of the article cited in footnote 1).

in a simple way. In order to do this, the intensity of the harmonics in the synthetic sound obtained is measured with a suitable analytic instrument, *i.e.* the synthesized function is again analyzed and compared with the intensity of the components of which the stencilled wave form is built up. The factor f_n is then equal to the ratio of the "apparent" (measured) and the "true" intensity [4]) of the n^{th} harmonic. In this experimental determination two other similar effects, but smaller than that of the finite width of slit are also taken into account, namely any slight deviation from straightness in the frequency characteristic of the amplifier and the slight lack of sharpness which occurs in the projection of the stencil on the disc due to the fact that the source of light is not a perfect point. The results of several measurements are given in *fig. 5*. These measurements were carried out with stencils of three different wave forms: a periodical repeated impulse with a width of 1/80 (a), 1/40 (b) and 1/20 (c) of a period respectively. The factors f_n so determined show very good agreement (fig. 5d).

In the experiments on synthetic sound the filter action of the disc, which is expressed in the factors f_n, may be entirely neglected, since one is almost always confined to the lower harmonics. In the rare case where many harmonics occur, for instance when the apparatus is to be used for a Fourier analysis, the filter action may be taken into account in two ways. The first is by making allowance for the filter action beforehand in cutting the stencil of the wave form, by dividing the prescribed intensity of every harmonic by the corresponding value of f_n [5]). The harmonics then occur in the output signal in the desired intensity. The second method is by allowing the frequency characteristic of the amplifier to rise at higher frequencies in such a way that the filter action of the disc is exactly compensated. Such a frequency characteristic can be realized in a relatively simple manner.

The wave form obtained is checked with a cathode ray oscillograph which is connected to the terminals of the loud speaker (figs. 1 and 2).

[4]) These terms are borrowed from a problem of spectroscopy which is closely related to ours, where one speaks of true and apparent intensity distribution of spectral lines. H. C. Burger and P. H. van Cittert, Z. Physik **81**, 428, 1933.

[5]) In using the experimentally found factors f_n it must be kept in mind that they represent an average value. The slits cannot be sector-shaped, as has been assumed in our considerations, but they have the same width over their whole length in order to ensure a linear relation between the amount of light transmitted and the height of the part of the stencil cut away. This has as a consequence that in the outermost part of the disc the ratio of width of slit to separation ($\theta/2\pi$) is smaller and the resolving power thus greater than in the inner part.

In *fig. 6* a number of wave forms are given together with the corresponding stencils and the oscillograms obtained. The latter were obtained without any correction being applied.

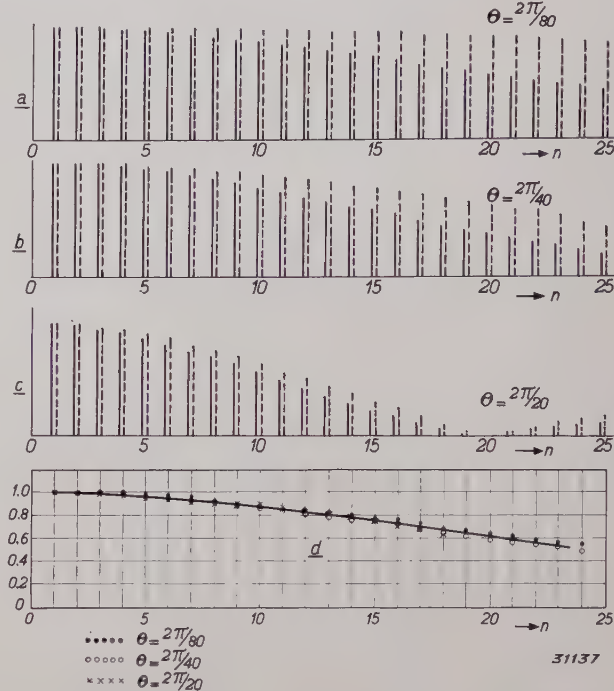

Fig. 5. True (broken line) and apparent (continuous line) intensity of the harmonics measured for three different wave forms: periodic repeated impulse with a width of a) 1/80 period, b) 1/40 period, c) 1/20 period; d) the factors f_n derived from the spectra a-c.

The only obvious deviation between oscillogram and required wave form is found in the case of the "square sine" (fig. 6b), where the horizontal parts are not quite horizontal in the oscillogram. This is due to the fact that the amplifier used does not pass the frequency zero. When a direct voltage is suddenly applied to the input terminals, a direct voltage also suddenly occurs at the output terminals, which, however, gradually falls to zero. Over against this statement it might be maintained that as soon as one passes over from the single commutation phenomenon to the periodic one, the frequency zero no longer occurs. It must, however, be kept in mind that the failure of the amplifier to pass the frequency zero is accompanied by a slight phase rotation of the lower harmonics. When this is studied it is found that the effect of this phase rotation is manifested in a slope of the horizontal parts of the wave form as may be observed in fig. 6b.

The influence of the phase of the different components of a sound on sound perception

According to a law of acoustics, which was formulated by Ohm, a definite pure tone will be

observed in a synthetic sound, when a component of the frequency in question occurs in the Fourier analysis of the wave form. According to a rule proposed by Helmholtz the sound perception will further depend entirely on the relative intensity with which the different components occur and will be independent of the relative phase of these components.

These facts are accounted for in a simple way by the assumption (which seems to be permissible anatomically also), that there are in the ear a large number of resonators tuned for different frequencies. This mechanism explains in the first place the fact that the ear carries out as it were a Fourier-analysis of the sound, while it furthermore makes it possible to suppose that the stimuli which are sent from each resonator to the brain depend exclusively upon the intensity and not upon the phase of the component in question, or at least that the phase does not finally reach conscienciousness.

This rule can be tested in a simple way with the help of the apparatus described above. For this purpose stencils of two different sinusoidal components are placed in the two holders H_1 and H_2. By turning the holder H_2 it is possible to change the relative phases of the components at will while listening to the sound obtained. It was never possible to discern any influence of phase on sound perception [6]).

This method can no longer be applied practically for phase rotations of a large number of components. It is, however, technically as well as theoretically important to find out whether in extreme cases, with wave forms having a large number of components, Helmholtz's rule remains valid. For instance, in amplifier technology upon the occurrence of grid currents a sharp peak appears in the output signal at a definite point in each period with a purely sinusoidal input signal. Thus in addition to the desired vibration a periodic impulse occurs which, as already explained, consists of a very large number of harmonics.

In amplifier technology it is customary to characterize the non-linear distortion of the out-

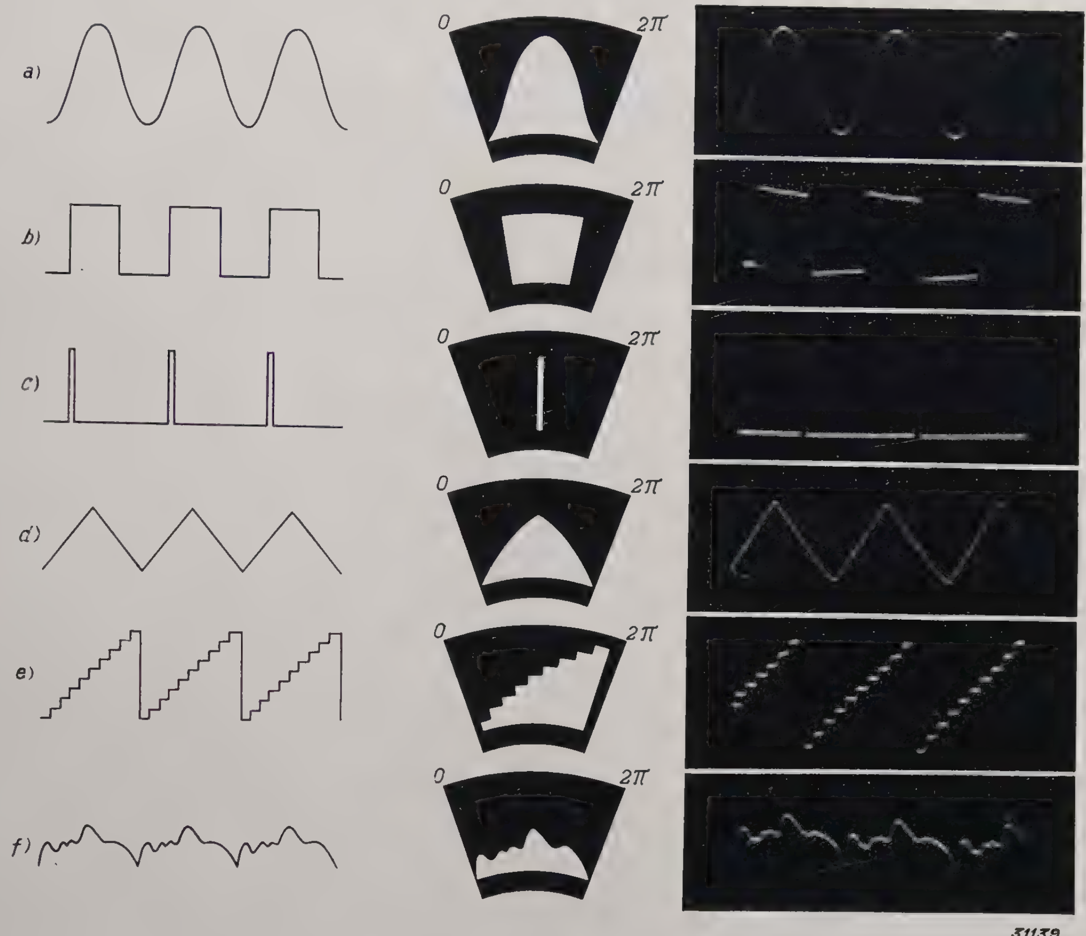

Fig. 6. Different wave forms with the corresponding stencils and the oscillograms obtained. The form a) is a pure sine curve, f) has the form of a profile of a human face.

[6]) Except in one very special case which we shall return to later.

put signal occurring in an amplifier by the distortion factor:

$$F = \frac{1}{a_1}\sqrt{a_2^2 + a_3^2 + a_4^2 + \dots} \quad . \quad . \quad (4)$$

a_1 here represents the amplitude in the output signal of the frequency fed to the amplifier, while a_2, a_3, a_4 represent the amplitudes of the higher harmonics formed. It may be seen that the phase of the harmonics is not taken into account. The quantity F will only be a useful criterion of the change in sound perception when Helmholtz's rule has also been found correct for a very large number of components.

We have studied this problem for the abovementioned case of the very narrow periodic impulse, and for this purpose we calculated four wave forms which were composed of the components cos $(n\varphi + \gamma_n)$ in practically equal intensity for $n = 1$ to $n = 20$. In the first form γ_n was always taken equal to zero, so that in the first approximation a periodic repeated impulse results. In *fig. 7a* the oscillogram of the wave form which was obtained is represented together with the spectrum of the harmonics which were measured in the sound produced. The three other wave forms which were built up of the same harmonic are shown in fig. 7*b*-*d* and explained in more detail.

It was found that these four totally different wave forms were quite indistinguishable as to their sound impression.

Helmholtz's rule is therefore also confirmed for the extreme case of a very large number of harmonics. It is therefore permissible, in the determination of non-linear distortion, to confine oneself to the measurement of the intensity of each of the harmonics without paying attention to their relative phase.

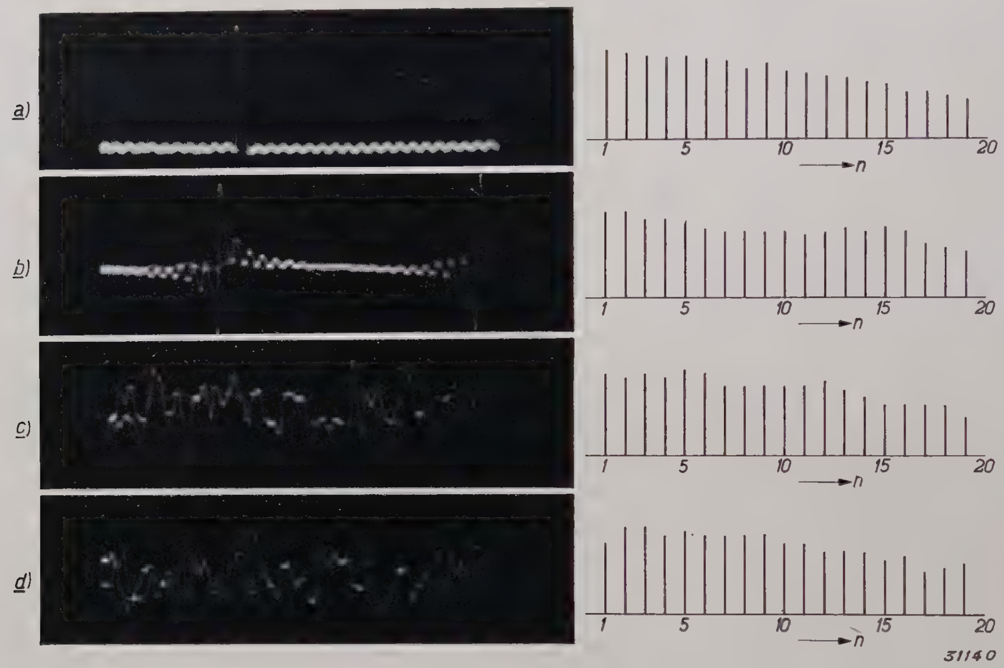

Fig. 7. Oscillograms and Fourier spectra of four different wave forms, all of which are built up of the same harmonic cos $(n\pi + \gamma_n)$ for $n = 1$ to $n = 20$. The four wave forms cannot be distinguished by ear.
a) $\gamma_n = 0$ for all values of n.
b) $\gamma_n = \pi/2$ for all values of n.
c) The 20 phase rotations, $\gamma_n = 2\pi/20, 4\pi/20, \dots 2\pi$, are distributed at random over the 20 harmonics, each phase rotation, however, occurs only once.
d) The phase rotations γ_n are chosen as multiples of $2\pi/40$, with an arbitrary series of numbers as factors (in our case the series of decimals of log 2).

Non-linear distortion in the ear

Non-linear distortion occurs in the ear. This distortion is manifested in the fact that when a pure tone of sufficient intensity is heard, higher harmonics are formed in the ear (the octavo, the duodecimo, etc.); when two tones of different frequency are heard at the same time, new tones are formed with frequencies which are linear combinations of the frequencies of the two tones heard (combination tones). The most obvious combination tone is the difference tone, and this is the one which was first discovered. One speaks of objective and subjective tones according as the tones perceived are

present or absent in the sound field outside the ear. With a single tone the occurrence of subjective harmonics can be perceived practically only as a gradually increasing sharpness of the character of the sound at greater sound intensities. When a second harmonic is formed in the ear (the subjective second harmonic), by which the resonator which is tuned to it is made to vibrate, we must expect that when we add a certain percentage of second harmonic to the physically pure tone (the objective second harmonic) it will be of some concern in what phase this occurs. This is therefore a deviation from Helmholtz's rule. Depending on the phase of the objective harmonic, it will be possible that the vibration of the resonator in question caused by the subjective harmonic will be either reinforced or weakened. It may even be expected that with suitably chosen intensity and phase of the objective harmonic a complete compensation of the subjective harmonic will occur.

This phenomenon can easily be investigated with the help of synthetic sound, by adding together the fundamental tone and its second harmonic with two stencils in the holders H_1 and H_2 respectively. If with a sound intensity of 106 phons (this corresponds approximately to the sound level of the noise in a boiler factory), 8 per cent of second harmonic is added to a tone of 200 cycles/sec (this case is represented in fig. 2), then when the holder H_2 is turned a change in the sound is very clearly perceived: at a definite position of H_2 (phase A) the sound becomes purer and weaker upon the addition of the objective harmonic; at a position which is shifted a quarter of a period with respect to the main tone (phase B) the sound becomes sharper and stronger.

We thus encounter an apparently paradoxal phenomenon, that a physically less pure tone sounds purer than a physically pure one, and that a tone makes a weaker sound impression after the objective addition of a certain amount of energy.

According to the above these phenomena can immediately be understood as an interference of the objective and subjective harmonics, whereby the vibration of the resonator of 400 cycles/sec in the ear is compensated in one case (phase A) and reinforced in the other (phase B). A further test of this statement is possible by generating a pure tone of for instance 406 cycles/sec with the help of a second loud speaker. If a tone of 400 cycles is present in the ear, beats will occur between this and that of 406 cycles. These beats can now be used to ascertain whether the above-described compensation actually takes place. When the objective sound is such that a tone of 400 cycles is no longer present in the ear (phase A), the beats must also disappear. This phase effect for the beats is actually found to exist.

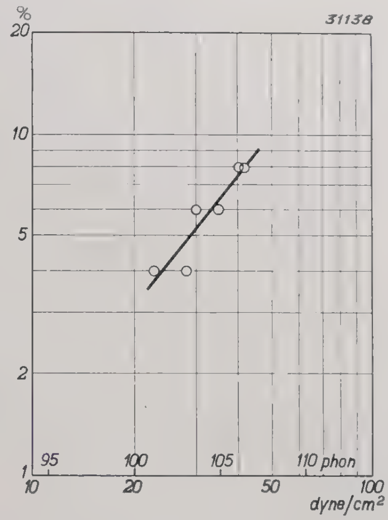

Fig. 8. Intensity of the subjective second harmonic in per cent of the intensity of the main tone, as a function of the sound intensity (sound pressure in dyne/sq.cm. and intensity level in phons).

The degree of non-linear distortion in the ear, *i.e.* the intensity of the subjective harmonic, depends upon the amplitude, *i.e.* the sound intensity of the main tone. Since the phase effect is most pronounced when objective and subjective harmonics have the same intensity, the above-described effects on the sound character, the intensity impression and the beats can be used as a method of determining the degree of non-linear distortion in the ear as a function of the sound intensity. In *fig. 8* are given the results of measurements by this method of the subjective second harmonic [7]).

It has been stated above that the presence of the subjective harmonics is manifested chiefly as a certain sharpness of the sound. If, however, the objective harmonic is adjusted to compensation, and it is then removed, it is found possible after some practice to bring into consciousness the subjective second harmonic separately in the physically pure tone. After several seconds, however, it seems to fade into the main tone and cannot be recalled again except after repeated comparison.

[7]) The results of the measurements carried out in this laboratory agree very well with those of Chapin and Firestone (J. Ac. Soc. Am. **5**, 173, 1933) and of Trimmer and Firestone (J. Ac. Soc. Am. **9**, 24, 1937). Measurements by Fletcher (J. Ac. Soc. Am. **1**, 311, 1929) carried out by a different method, and also those of von Békésy (Ann. Physik **20**, 809, 1934) gave much larger percentages than those shown in fig. 8.

THE WELL-LIGHTED HOUSE

by L. C. KALFF.

628.972

In order to demonstrate the effect of different lighting systems, a model house was designed in which modern methods of illumination have been generously applied. The house is furnished with colourless, stylized furniture. In this way the attention is not distracted from the main feature, the lighting, and the properties of the different methods of illumination are fully brought out.

Within the last few decades the demands made of artifical lighting have steadily increased, especially in the case of street lighting, shop window illumination, workshop lighting, etc. This increase has been less noticeable in the case of the illumination of the home. This fact is understandable since better street lighting makes for safer traffic, better lighting of workshops increases the speed of working and reduces waste, better lighting of shop windows induces buying, etc. In the home, however, the favourable results of better lighting cannot be expressed in terms of money, and the harmful effects of poor lighting on the eyes are difficult to prove. It is, however, thoroughly realized that a higher current consumption, and therefore greater expense, will result from an improvement in the lighting installation.

In addition to the strong resistance which must be overcome in this respect there is a serious technical difficulty. In workshops, offices and shops illumination for working purposes is the chief concern, and light-coloured walls and ceilings can be used in order to avoid too much contrast in brightness in the field of vision. Such contrasts in brightness are even less permissible because of the danger of glare, the higher the general level of brightness. In the home it is desirable to reach the relatively high intensities of illumination which are required for working purposes at certain spots only, while the atmosphere of the interior may not thereby be spoiled. Too high a general level of brightness, and at the same time too great contrasts must therefore be avoided. This requires much more care and offers many more difficulties than in the businesslike surroundings of our places of work.

It is impossible to give hard and fast rules for the installation of the lighting equipment in the endless variety of our living quarters. There is, however, a very great number of forms and ap-

Fig. 1. Hall of the "well lighted house". On the left the dining room and the bed-sitting room. In the background the bathroom. The hall itself is lighted by a dome and a niche in the wall to the left.

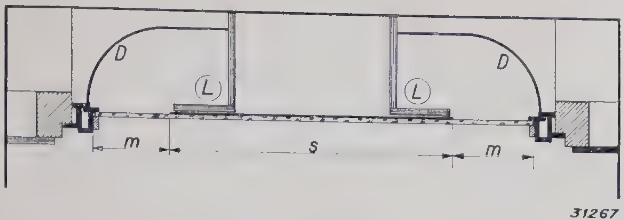

Fig. 2. Mirror with built-in illumination. *S* section of glass provided with a mirror, *L* "Spiralta" lamps of 15 Dlm (1 Dlm. = 1 dekalumen = 10 lumen), distance between lamps 23 cm, *0* diffusely reflecting white surfaces.

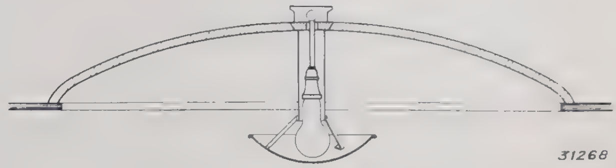

Fig. 4. Cross section of the dome in the hall. It has a diameter of 1.20 m and is made in advance of plaster and then placed on the ceiling. The bowl under the lamp (100 Dlm) is sprayed with white on the inside and dull nickel-plated on the outside. It is fastened at three points by bayonet fastenings and can therefore easily be removed for changing the lamp.

plications of different lighting fixtures available, which can be used in all varieties and combinations for the solution of this problem. In order to be able to avail oneself fully of these possibilities it is desirable to have several experimental and exhibition rooms in which as many as possible of the above mentioned lighting systems can be installed. As an example of such exhibition rooms a complex in the Philips demonstration halls has been fitted out as "The well lighted house".

Fig. 3. Hall of the "well lighted house", seen from the bathroom. In the background the kitchen. The treads of the stairs are lighted by lamps built in at the base of the bannister. The dummy figures in this house were designed by George Pål.

In designing such exhibition rooms the difficulty is to choose an interior such that every visitor will be able to make a comparison with his own home. One person will for example find that the rooms are too luxurious, and will thereupon conclude that the lighting installation is out of the question for his own case. Another will find in a piece of furniture or a rug, a colour or a shape so much to criticize or admire that he will entirely forget to notice the illumination.

In order to avoid this distraction from the main purpose an attempt is made to make the interior as "impersonal" as possible, without using real furniture which some will admire and others despise, without using colours and contrasts, period furniture and ornamental shapes, even without pictures on the walls, which might distract the attention from the main feature, the lighting. In order to accomplish this the following method was followed.

The furnishing is carried out entirely with stylized furniture, *i.e.* the pieces of furniture are reduced to their simplest forms. For example a chair has a rectangular back and seat, the legs are also rectangular, the table is a thick board on four straight legs. Colours are all replaced by greys and white. The normal differences in light reflection from different materials and surfaces are therefore transformed into different shades of grey. Five different shades are used with reflection coefficients of approximately 75, 60, 45, 25 and 10 per cent. A desk, which would ordinarily have the colour of oak, is painted with a grey paint which reflects 25 per cent, walls were given a reflection coefficient of 60 per cent, furniture was given different shades with reflection coefficients of 45 and 25 per cent for instance.

The effect was surprising, the rooms did not appear strange or unpleasant. Many visitors were even of the opinion that such interiors would prove satisfactory for normal use. It was, however, especially gratifying to be able to ascertain that the effect of the different lighting systems was tho-

Fig. 5. Living room. General semi-indirect illumination by a central ornament made of parchment, 3 lamps of 100 Dlm (Dlm = dekalumen = 10 lm). Local illumination for reading and sewing from a standard lamp "Philihome" 50 with a lamp of 200 Dlm, 150 W. Intensity of illumination on the reading matter 300 lux. A wall illumination behind the couch decreases the contrasts in the room.

Fig. 6. The same room as in fig. 5, but with different illumination. General, completely indirect illumination by means of a trough above the hearth. There are nine "Cornalux" lamps of 60 W built into the trough. The "Cornalux" is a lamp of special shape which is partially silvered. It makes it possible to distribute the light very uniformly over the ceiling and to construct indirect illumination systems with a very high efficiency. Semi-indirect illumination by means of a trough above the curtain, provided with patterned frosted glass. Auxiliary illumination behind the couch, above the doors and in the niche above the hearth.

roughly brought out, and that this was one of the main factors in the impression made by the interiors. This makes it possible for the visitor to judge the practical and decorative result of a system of illumination.

We shall now describe several of the rooms, and in doing so we shall deal with several general factors which are important in designing a lighting system.

Everywhere in the house an attempt has been made to install the amount and kind of light which would be needed there. A good illumination of the doorstep with or without an illuminated house number has not been forgotten.

Opposite the front door in the hall a niche has been made which is lighted from both sides (see *fig. 1*). This serves as substitute for a window in this small windowless hall.

On the right of the front door, invisible in fig. 1, a mirror has been built into the wall. The lighting of this mirror is shown in *fig. 2*. The middle section of a large plate of glass has been given a mirror back, the two strips on either side have been frosted. Behind these strips are bent surfaces lighted by a row of lamps. Anyone standing in front of the mirror is thus illuminated indirectly and from all sides, so that no shadows can spoil the visibility.

All the lights can be switched on and off by the visitor by means of a series of switches. Beside each switch may be found a brief description of the installation which it operates, as may clearly be seen in *fig. 3*.

As an example of the attractive effects which can be obtained when it is possible to make allowance for the lighting system during the construction of the house, may be mentioned the small plaster dome (fig. 3 and *fig. 4*) which gives indirect lighting of part of the hall, and the built-in stair lighting along the base of the stair bannister which only lights the stair treads. In more modest houses also such lighting features can be introduced without great expense, and we believe that they would considerably increase the attractiveness of such houses.

In the background of figs. 1 and 3 may be seen the bathroom and kitchen respectively, which we shall not describe in detail.

On the right next to the kitchen is the living room which is shown in *fig. 5*. A central fixture for semi-indirect lighting, as used in this room, may give a good general illumination in such a room of modest dimensions. Since, however, the occupants ordinarily sit facing the light, it is usually insufficient for reading or sewing. One needs 150 to 200 lux on the piece of work or book, and in

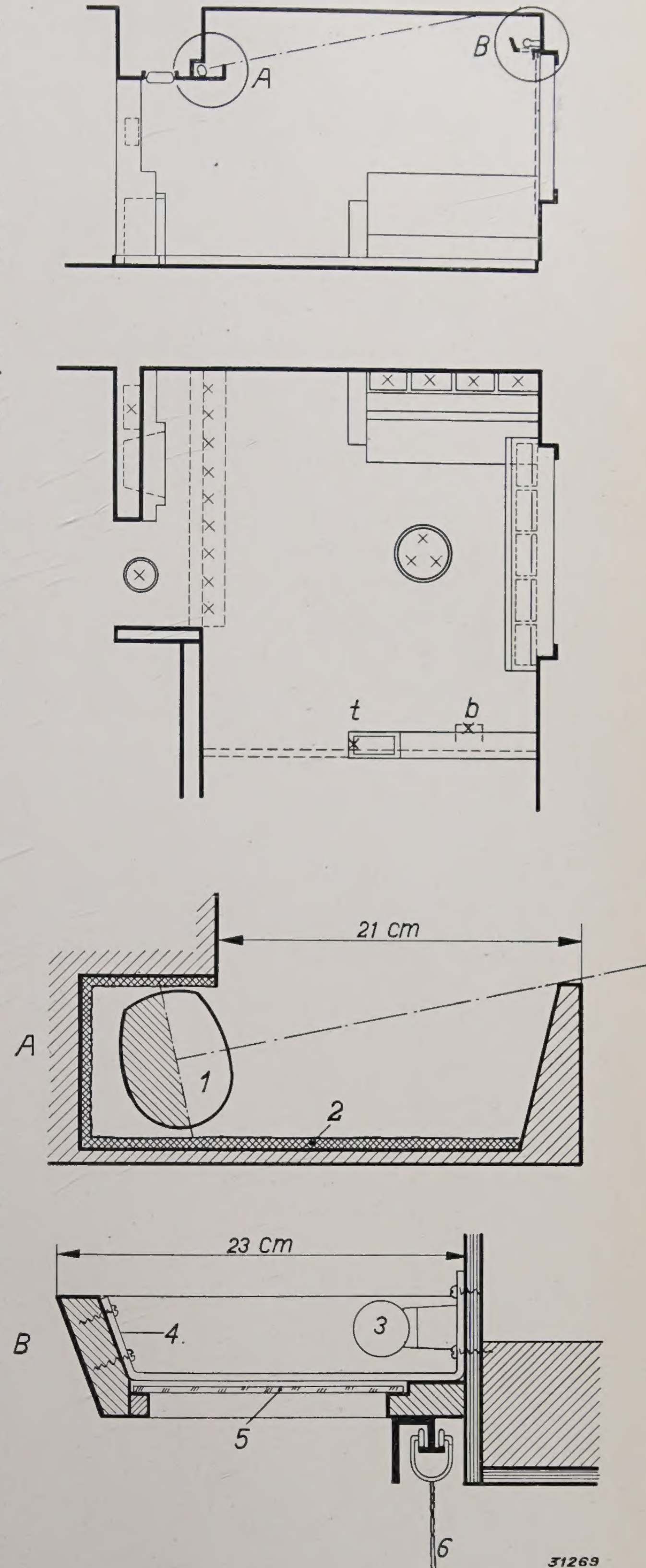

Fig. 7. Diagram of the cross section and view from above of the illumination systems in the living room. In addition to the systems shown in figs. 5 and 6 the illumination of the bookcase (b) and the teatable (t) are indicated by crosses. The illumination over the hearth (A) and above the curtain (B) are then given in more detail. *1* "Cornalux" lamps 60 W, distance c.o.c. 33 cm; *2* asbestos; *3* "Philinea" lamps 40 W; *4* white painted surface; *5* patterned frosted glass; *6* curtain.

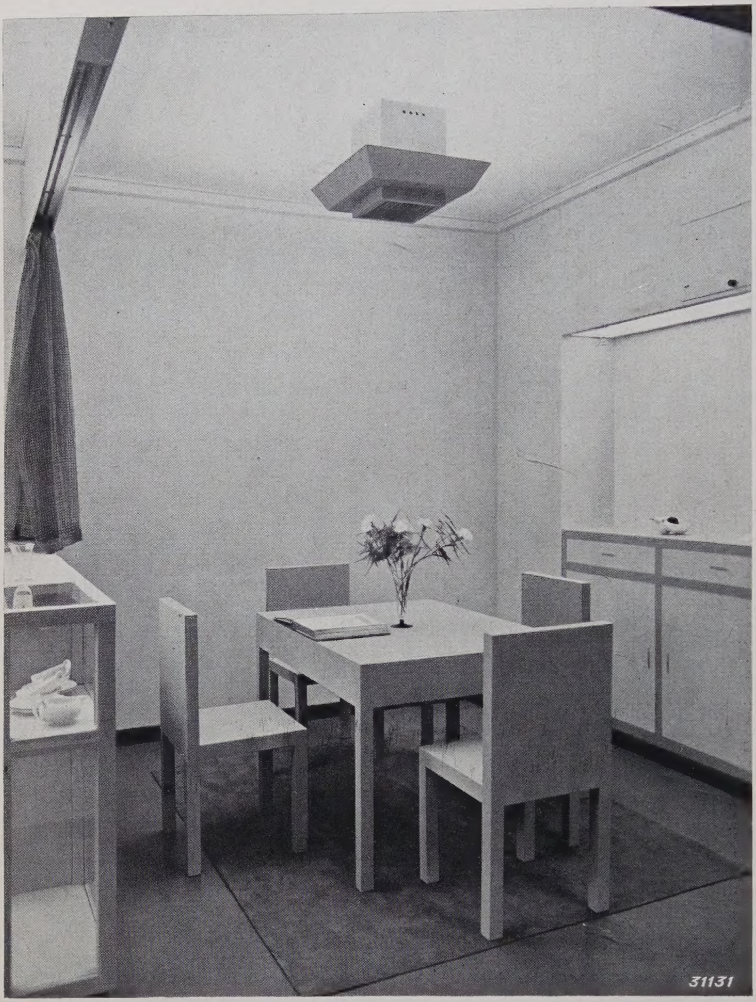

Fig. 8. Dining room. Indirect illumination with four "Cornalux" lamps of 60 W. Illumination above the sideboard by five lamps of 25 Dlm above a plate of frosted glass. Direct illumination, directed on to the table, from a mirror reflector "Philiray" SC 255 with an "Argenta" lamp of 200 W. The average intensity of illumination on the table is 250 lux. This light is not on in the photograph, but it may be seen in fig. 1.

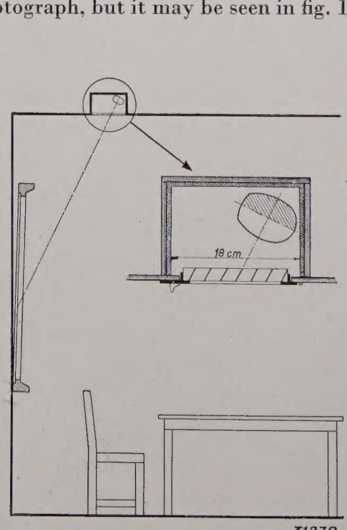

Fig. 9. Illumination of a picture in the dining room by a "Cornalux" lamp of 100 W, built into the ceiling. The lamp is hidden by a grid of steel strips. The light is directed on to the picture at a slight angle so that the latter cannot reflect.

order to attain this the central light point would have to be so large and intense that it would be disturbing.

For this reason local auxiliary lights are to be recommended. In this case a standard lamp has been placed near one of the arm chairs. Together with the centre light this gives 250 lux upon a book held in the hands of the occupant of the chair.

When the reader looks up from his book the great contrast between the bright surfaces of the book and the lighting fixture, and the relatively dark surface of the much less strongly illuminated wall will give a somewhat unpleasant impression. It is striking how much the impression of the room improves when for example the wall lighting behind the couch is switched on, or the curtain illumination which is introduced behind a simple wooden frame with frosted glass, above the wide light-grey velvet curtain.

In some cases in such small rooms the great size of the central lighting fixture is a serious obstacle in making the best use of the space available. Especially in the daytime these useless large volumes are real nuisances. Built-in niches or light panels in pieces of furniture, light coves and niches are much smaller and can usually be constructed to be quite unnoticeable.

As an example of such a feature, in addition to the central lighting fixture, another kind of general illumination may be used in the living room. This is an indirect illumination installed in a light cove above the hearth (see *fig. 6*). This gives an average intensity of illumination of 90 lux. With this general illumination, local illumination for instance of the niche by the hearth, of the bookcase or the teatable, is also very convenient and attractive.

All these systems of illumination can be relatively simply made, the construction of several of them is indicated in *fig. 7*, and they will in many cases cost no more than a good chandelier or table lamp, with which it would be very difficult to obtain the same effect.

The dining room, which is shown in *fig. 8* and fig. 1, presents quite a different problem. In the first place the table must be very well illuminated, preferably direct and with some reflexes in order to bring out the beauty of crystal and silver on the table. For this purpose a very simple wooden ornament in the ceiling which occupies little space

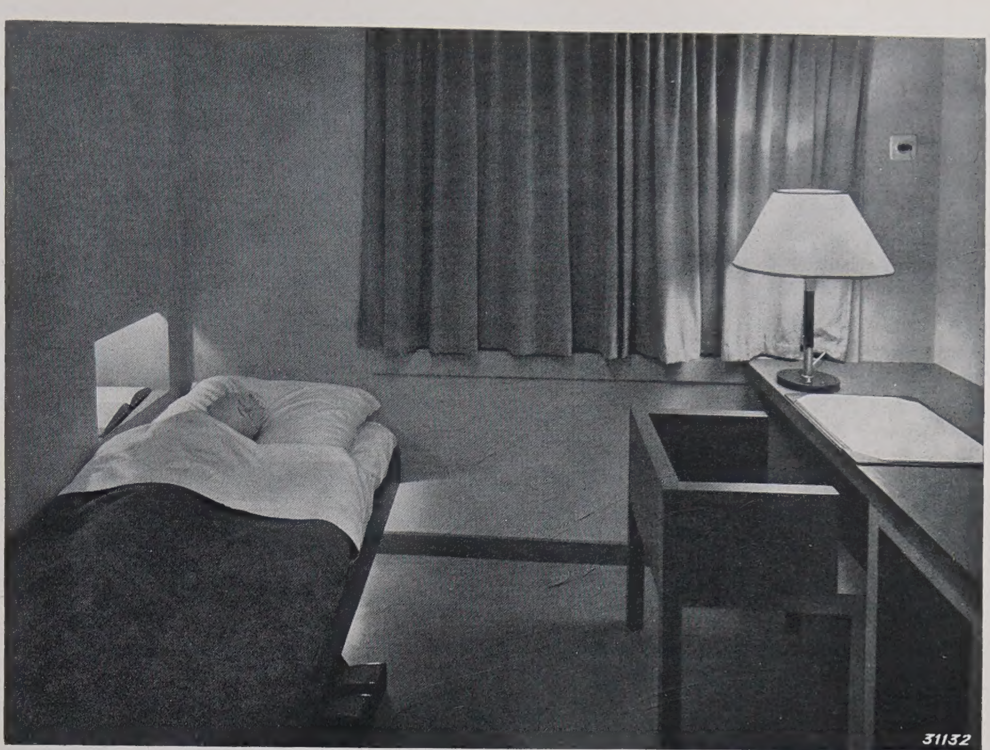

Fig. 10. Bed-sitting room. General illumination by a ceiling fitting (see fig. 1). Auxiliary illumination in a niche beside the bed, also under the bed and on the desk.

has been chosen. It is obvious that this ornament could be made more decorative in form and material in many ways. A silvered reflector with a large lamp is placed in a square box. This is screened by vertical louvres. The light thus falls chiefly in a vertical direction and gives an illumination of about 250 lux on the table top.

With this light alone the contrasts between the strongly illuminated table cloth and the walls would be too great. An auxiliary illumination, for instance in a niche above the sideboard, immediately improves the atmosphere of the room. Moreover there is the advantage that any one busy at the sideboard need not work in his own shadow.

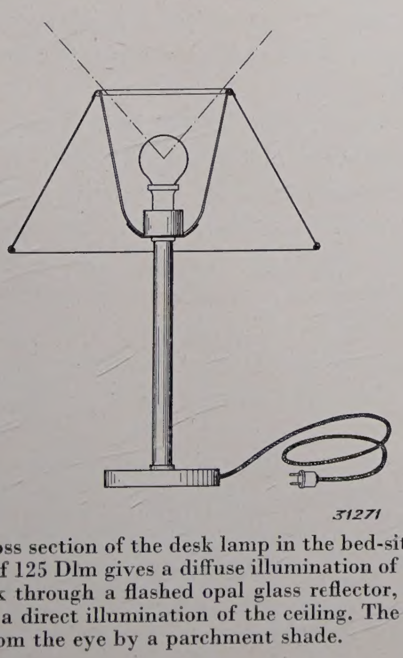

Fig. 11. Cross section of the desk lamp in the bed-sitting room. The lamp of 125 Dlm gives a diffuse illumination of the surface of the desk through a flashed opal glass reflector, and at the same time a direct illumination of the ceiling. The reflector is screened from the eye by a parchment shade.

As alternative, or together with the direct illumination of the table, a light recess is made around the central reflector. An indirect illumination is built into this which gives the entire room an additional illumination of 75 lux at table height. This indirect illumination is more restful and more diffuse than the direct illumination, and will be used especially when the room is not being used as a dining room, but for childrens' home work or for reading at the table. In fig. 8 the indirect illumination is on, while in fig. 1 the direct illumination is being used.

Finally a small source of light is let into the ceiling by which the empty rear wall of the dining room can be lighted. This light (see *fig. 9*) is meant to be used when a picture is hung on this wall. It is a fact that the eye is always attracted to the brightest spots. When a picture hangs on a light-coloured wall, a conflict arises, because the wall is the lighter and thus attracts the eye, while the picture, which usually contains much darker colours and thus forms a less bright spot for the eye, should be receiving the attention. If now the surface of the picture is extra strongly illuminated locally, for instance by 80 lux, this conflict is removed and the picture comes out much better. In the combination bed-sitting room partially visible

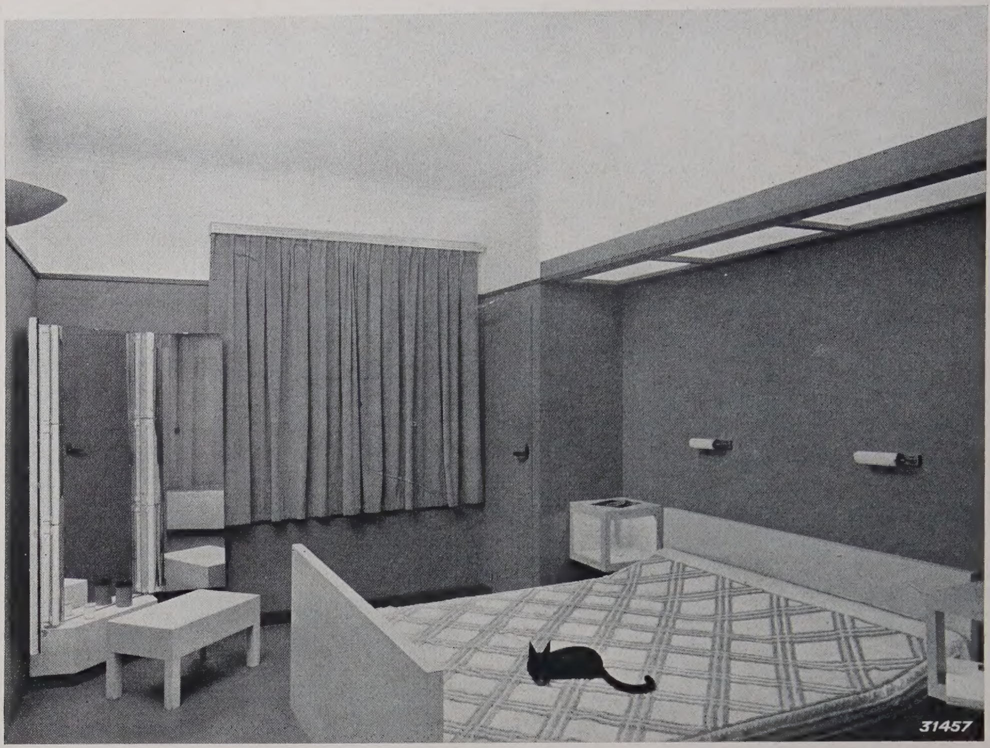

Fig. 12. Bedroom. General illumination installed between two wall closets behind frosted glass. Auxiliary illumination of the ceiling by a reflector on the opposite wall. Illumination of the mirror by tubular lamps at either side. Illumination of the bedside tables and of the wall closets.

in fig. 1 to the right of the dining room, various lighting features have been installed which contribute very much to the comfort of such a room. The general illumination is by a ceiling fitting which, however, in order to avoid too much severity, is set in a circular depression in the ceiling. A very attractive effect can be obtained by giving the surface of this depression a very light colour.

In *fig. 10* the bed-sitting room is shown separately. Next to the bed is a lighted niche with room for a clock, which makes it possible to read in bed. A small lamp has been installed under the bed which lights the floor sufficiently so that one can find ones way about the room without disturbing the sleeper. This is especially important in a child's room or a sickroom.

On the desk stands a good table lamp which is shown in cross section in *fig. 11*. This lamp contains a source of 125 Dlm (1 Dlm = 1 dekalumen = 10 lm) and gives on the surface of the desk at 30 cm distance an intensity of illumination of 300 lux, at 50 cm 200 lux and at 50 cm 110 lux. The light is scattered diffusely by a milk glass screen built into the shade. This milk glass screen serves at the same time as reflector and gives an indirect illumination *via* ceiling and walls, so that the whole room forms a bright pleasant background for the brightly lighted working surface.

The last room of the series, the bedroom is lighted mainly indirectly from a light trough above the bed (see *fig. 12*). This trough is hung between two wall closets and covered at the lower side with frosted glass. In this way there is somewhat more light at the head of the bed than the general level of illumination of the room, and the intensity is high enough to make it possible to read in bed. Nevertheless there is no light shining directly in the eyes when one lies in bed, as there would almost certainly be in the case of a hanging central ornament.

The large mirror is flanked on both sides by tubular lamps along the whole length. This provides a very generous illumination of 400 lux on the person standing before it. It is striking that the image in the mirror becomes much more satisfactory when the background, *i.e.* the wall opposite the mirror, is well lighted. This means that the contrast between the tubular lamps and the background which is reflected should be made as slight as possible.

Lamps are installed in the wall closets which are lighted automatically when the door is opened. The advantage of this closet illumination is obvious; without such illumination one always stands in one's own light when using the closet.